The Construction and Demolition Waste Management in Malaysia: The Life Cycle Assessment Analysis Approach to Sustainability

マレーシアにおける建設廃棄物マネジメント：持続可能性へのライフサイクルアセスメントアプローチ

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ABSTRACT

Construction and demolition waste (C&DW) continues to increase in parallel with economic growth in emerging and developing countries like Malaysia. The large amount and improper management of C&DW generated during construction often results in considerable environmental impact. Although much of the C&DW material is inert, non-hazardous, and does not produce greenhouse gases (GHG) in landfill, the amount of C&DW quickly depletes the finite land resources. Notwithstanding legislation (Solid Waste and Public Cleansing Management Act 672) governing solid waste management in Malaysia, C&DW attracts significantly less attention than other forms of waste, such as municipal solid waste and hazardous waste. Malaysia's goals are aligned with UN Agenda on "The Sustainable Development Goals: A Universal Push to Transform Our World" through the current five-year development plan, the 11th Malaysia Plan (11th MP). On climate change, Malaysia is committed to reducing the GHG emission intensity as ratio of its GDP by 45% by the year of 2030. Though the 11th MP only briefly addresses waste management, reusing and recycling of C&DW may contribute to GHG reduction goals, including by reducing the need to harvest new raw material.

This waste generation study offers a theoretical method in estimating the C&D waste generation rate by utilizing project site waste records, site survey, and information from waste management plans. The WGR refers to the estimated amount of waste created by a construction project, based on its constructed or demolished floor area. The theoretical method, known as point source waste assessment, is applied to eleven projects across Malaysia as case studies, sampling different construction methods. The WGR is found to be 9.85 t /100m2 in the conventional construction method. The mixed construction method demonstrated the lowest WGR at 3.29 t /100m2, while demolition project WGR was 104.28 t /100m2. Using the average WGR data collected from the eleven C&D projects, this study forecasted the total national C&D waste generation through 2025 based on application of statistical data of projected housing supply and demand. By understanding and predicting C&D waste generation, stakeholders can make decisions that may be both economically and environmentally optimal.

The second objective of this study is to investigate the potential environmental impact and GHG emissions associated with the C&D waste material. The environmental impact assessment is done through life cycle assessment (LCA). A comprehensive LCA

framework assessed the environmental impact associated with the upstream and downstream of C&DW material's life cycle. The scope of this LCA ranged from raw material extraction through material processing and distribution, to end-of-life disposal, whether through landfill or recycling. C&DW materials were evaluated with different system boundaries highlighting the alternatives in waste management. The system boundaries and waste scenarios address the consequences of possible decisions, parameters, and alternatives. The LCA study is divided into three chapters that offered interesting outcomes to better manage C&DW:

- Wood waste LCA, demonstrating the option of energy recovery from waste recycling;
- Concrete waste LCA and LCC, demonstrating the combination of environmental and economic indicator in influencing the decision making process in waste management; and
- Mixed C&D waste LCA, demonstrating the waste disposal scenario as the end-of-life and identify the optimal solution to manage the mixture of C&DW.

In wood waste LCA, a similar LCA framework was designed for assessment of the environmental impact associated with different scenarios of wood waste management strategy. This research design targeted to investigate the wood waste in three scenarios: landfilling, recycling for biofuel material, and combusting or incinerating wood waste. Wood waste is assessed within a study boundary that included energy recovery, depicting the waste management possibilities in contributing to energy recovery industry. The ideal scenario is incineration with energy recovery, followed by recycling or reuse as biofuel material, with landfilling contributing the most to GHG emissions. Results from the wood waste LCA suggested energy recovery would likely offset the environmental impact caused by landfill.

Concrete waste is assessed based on eco-efficiency indicators which included the LCA and life cycle costing (LCC) analysis. The economic impact serves as an extra indicator influencing a decision making processes. In concrete waste LCA, the economic feasibility analysis and the life cycle impact assessment of recycling and reusing concrete waste material were studied. There are four scenarios in this research design. Scenario 1 depicts the cradle-to-the-grave scenario (landfilling) while scenario 2, 3, and 4 depict the cradle-to-the-cradle scenarios (recycling) in which the concrete waste is recycled into aggregate and reused as road base material and reused to reproduce new concrete. Life cycle inventories include GHG emission and costing from mining, processing, distribution, disposal, and recycling processes. Data were collected through survey and interview. Ecoinvent 3.3 database was used to replace the missing primary data. The main outcome of this study highlighted the importance of concrete waste recycling towards achieving a higher eco-efficiency decision in reducing the environmental impact and cost associated in landfilling. Recycling scenarios produced significantly lower GHG emissions and have lesser cost impact as compared to the landfilling scenario. Concrete waste is preferably used as substitution of the natural aggregate to reduce the mining activity and the new raw material. While the environmental impact is an integral part of sustainability, overall feasibility of a waste management plan requires consideration of economic impacts. The concrete waste LCA and LCC illustrated where economic and environmental considerations may harmonize in environmentally sound and cost-effective concrete waste management.

Mixed C&D waste is assessed within a study boundary that reflects the actual industry practice of disposing waste without separation. The purpose of this study is to investigate the consequences of specific discrete assumptions and parameters in influencing the existing landfilling system. Eight what-if scenarios were built to illustrate a number of plausible parameters and routes that pose challenges for waste recycling business. The scenarios were built based on three parameters: i) maximum (100%) diversion of waste into recycling stream, ii) reduce travel distances and placement of material recovery facility (MRF) within three kilometers from construction site, and iii) waste reduction through shifting of construction method to industrial building system (IBS). The sensitivity study shows that the outputs are sensitive to the savings made in the three parameters.

This study projected the total waste generation to predict the GHG emission caused by C&DW up to year 2025. C&DW is estimated to increase 21.2 % from 2016 to 2025 if current practices continue. GHG emissions that increase along with total amount of waste generation in 2025 were predicted. Maximum diversion of C&D waste to recycling instead of landfilling could reduce 24.2% of GHG emissions and reduce 61 % of land occupation. Reducing travel distances between waste source and destinations could further reduce 51.2 % of GHG emissions and increase savings in land occupation by 75%. A shift of construction method from conventional construction method to industrial

building system (IBS) could potentially reduce the amount of C&D waste generated and eventually reduce the GHG emissions to 96 % and reduce 99 % of associated land occupation.

Global GHG emissions growth may seem inexorable, but mitigation through choosing a low impact waste management scenario could help developing countries like Malaysia in decoupling economic growth from the GHG growth. This study concluded with the discussion and further research in developing a sustainable C&D waste management plan that embraces sustainable development stewardship.

Keyword*: Construction and demolition waste, waste generation rate, life cycle assessment, life cycle costing, economic impact, environmental impact, decision making, GHG emissions*

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For my family, Richard, and Opa Bergermann.

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List of Abbreviations

AMQ	aggregate mining quarry
C&D	construction and demolition waste
CBP	Concrete batching plant - is where the new concrete and recycled aggregate concrete (RAC) were produced. RAC were produced by using RCA
CCM	conventional construction method
CS	construction site - the waste producer / the origin of the concrete waste flow start from construction site
CW	concrete waste
HRMUD	high-rise mixed-use development
IBS	Industrialized building system
LCA	life cycle assessment
LCC	life cycle cost
MCM	mixed construction method
MRF	material recovery facilities - concrete waste is sent into MRF for recovery and recycling
NA	natural aggregate produced from mining
RAC	concrete produced by using recycled aggregates concrete (RAC) or combinations RCA with natural aggregate (NA)
RCA	Aggregates produced by crushing the concrete waste. Recycled concrete aggregates may be referred to as recycled aggregates too.
RCS	road construction site - the site where recycled concrete aggregate (RCA) materials were used as road base material, replacing the demand of natural aggregate
S1	Scenario 1
S2	Scenario 2
S3	Scenario 3
S4	Scenario 4
WGR	waste generation rate

1 Introduction

This thesis studies on the management and the environmental impact of construction and demolition waste (C&DW) in Malaysia. This study includes the waste generation rate, estimation of future waste generation, and it environmental impact assessment.

The construction industry plays a crucial role in Malaysian economy growth. The industry currently contributes 4 % to the Malaysian Gross Development Product (GDP) and it is expected to continues to contribute 5.5 % to the GDP in 2020 (Bank Negara Malaysia & 11th Malaysia Plan, 2011). Construction industry in Malaysia consumes around 15 % of total manufacturing output, with more than 120 industries relying on construction industry for their growth and sustainability, making it a two-times multiplier industry. It also provides 9.5 % of Malaysia's total workforce, includes professionals, skilled, and non-skilled workers (DOSM, 2013). The significance of the industry will continue to grow and it will become increasingly critical as Malaysia transform into a developed nation by 2020. The industry demonstrates strong correlation with economic development, with the construction share of GDP positively correlated with GDP per capita.

Despite many initiatives and program being implemented in Malaysia, the industry is still facing issues such as quality workmanship, safety awareness, labor shortages, complex bureaucratic and regulations procedure, and public perception toward the industry. The current issues in the industry include natural disaster resiliency, green building, low carbon material, sustainable construction, and high contribution of construction waste to landfills. The construction industry has continued to expand with the global economy as a driving force in the transformational growth into developed economies; the industry has now become a significant consumer of new material and major solid waste contributor.

Malaysia's goals are aligned with UN Agenda on "The Sustainable Development Goals: A Universal Push to Transform Our World" through the current five-year development plan, the 11th Malaysia Plan (11th MP). On climate change, Malaysia is committed to reducing the GHG emission intensity as ratio of its GDP by 45% by the year of 2030. Though the 11th MP only briefly addresses waste management, reusing and recycling of C&DW may contribute to GHG reduction goals, including by reducing the need to harvest new raw material.

The research question is how do C&DW waste management practices achieve sustainability to reduce its environmental impacts and to contribute to GHG emissions mitigation. The specific research questions are:

i) What is the amount of C&DW generation now and in future?
ii) What is the environmental impact associated with different waste management strategy?
iii) What is the best waste management alternative in managing C&DW to minimize the environmental impact and GHG emissions?

The goal of this study is to develop a sustainable construction and demolition waste management plan, and to answer to the research questions. There are three primary objectives in achieving the study goal:

i) to estimate the waste generation rate (WGR), to determine the waste composition, and to forecast the future, 2025 total waste generation,
ii) to investigate the potential environmental impact and GHG emissions associated with the C&DW material in different waste management strategy and disposal scenario, and
iii) to forecast the environmental impact and GHG emissions caused by C&DW up to year 2025.

A complete C&DW management system that proactively gather, store, and analyze large data sets including waste type, waste generation rate, waste flow, and other environmental impact data is vital in supporting the decision making. A quantitative database is crucial in assisting stakeholders in making data-driven and sound-science decisions to achieve sustainability.

The outline of this thesis included the overview and methodologies in Chapter 2. Chapter 3 described the estimation of waste generation rate and chapter 4 described the projection of future (2025) waste generation based on the result from chapter 3. Chapter 5 reviews the life cycle assessment (LCA) method. Chapter 6, 7, and 8 uses the results obtained from Chapter 3 and 4 as the base data in estimating the environmental impact and GHG emissions with using LCA approach. Chapter 6, 7, and 8 were written as independent research manuscript evaluating different LCA system boundaries that were built closely related to the LCA goal definition. Chapter 6 and 7 focused on the two most recovered C&DW materials, wood waste and concrete waste. Wood waste LCA evaluated waste management preferences according to waste hierarchy in three scenarios includes a hypothetical incineration with energy recovery. Chapter 6 evaluated the feasibility of concrete waste management through environmental LCA and life cycle cost (LCC). The system boundary is expanded to include the reusing and recycling of waste material to substitute the upstream raw material extraction. Chapter 8 described the environmental impact and GHG emissions of C&DW material as mixed C&DW where separation and recovery process occurs in material recycling facilities (MRF). This chapter study focused only on the end-of-life waste disposal stage. This chapter combined the year 2025 waste generation data from chapter 3 and 4 to model the future waste management scenarios and identified the optimal waste management scenario. Conclusions are drawn in the final chapter 9 (Figure 1).

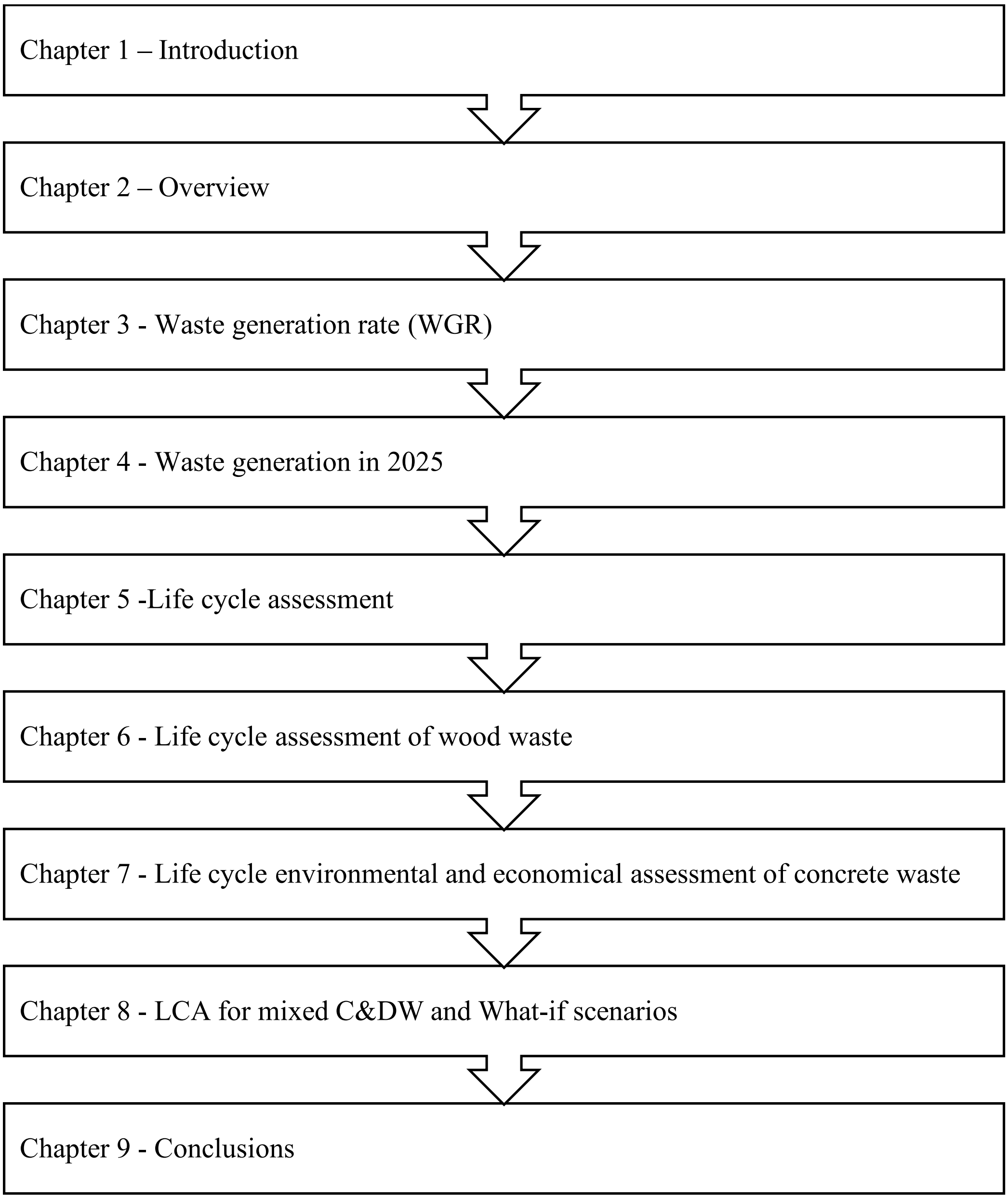

Figure 1: Research flow framework

2 Literature Review and Research Methodologies

2.1 Construction and Demolition waste in Malaysia

C&DW continues to increase in parallel with the economic growth especially in the emerging and developing countries like Malaysia, of which little of it is recycled. The waste management in Malaysia is principally driven by profit and economic incentives with low dumping cost and abundant in natural resources resulting in large-scale C&DW dumping, particularly illegal dumping (Mah, Fujiwara, & Ho, 2017). There are 851 illegal dumpsites by the road were identified in 2015. The current dumping and landfilling methods cannot sustainably address the increasing rate of C&DW generation (Fauziah & Agamuthu, 2003), making it crucial that recycling alternatives be explored. Even though most C&DW material is inert, non-hazardous, and does not produce GHG in landfill, it occupies significant volume of finite landfill land and entails significant GHG emissions from landfill transportation. Unstable waste deposit and inappropriate management further threatens the landfill slope stability and could risk catastrophic environmental disaster. For instance, an illegal construction landfill in China collapsed, claiming 75 lives and damaged properties (Duan & Li, 2016).

Statistics show that waste generation from the industry has significantly increased. The United States Environmental Protection Agency (USEPA) estimates that 170 million tons of building-related C&DW materials were generated in 2003 (USEPA, 2003) and it was 200 million tons per year in 2016 (USEPA, 2016a). Meanwhile in the European Union, the industry contributed 33% (of 821 million tons) of the total waste in year 2012 alone (Eurostat, 2015) with UK contributing 110 million tons per year (EU, 2011). France alone generates around 250 million tons per year (EU, 2011). Fifty percent of the total waste generated in United Kingdom is C&DW, with the discharge amount estimated at 70 million tons per year (Sealey, Phillips, & Hill, 2001). In Hong Kong, it is estimated at 23%, which amounts to 20 million tons (Poon & Chan, 2007). The C&DW generation in a developing country like Malaysia is reaching parity with that of developed countries, C&DW accounts for approximately 41% of total solid waste generation (Eusuf, Ibrahim, & Islam, 2012). Malaysian C&DW is estimated at 161.19 tons per day in 2009, increasing to 299.69 tons per day in 2015, and is projected to reach 368.31 tons per day by 2023 (Fauziah & Agamuthu, 2003).

In developed countries, recycling of C&DW is regulated by laws and regulations and the recycling rates have far surpassed 90 %. In Australia, it recycled almost 90 % of waste generated (Zealand, 2011), Japan recycling rate is 99.5 % in 2012 (MLIT, 2014), and Singapore too demonstrating the highest recycling rate of 99.9 % (NEA, 2016). Malaysia's C&DW recovery rate remains at less than 50 % (UNCRD, 2015) a poor level attributed to a lack of institutional supporting policy, recycling programs, and recycling facilities in major cities.

Notwithstanding legislation (Solid Waste and Public Cleansing Management Act 672) governing solid waste management in Malaysia(National Solid Waste Management Department, 2007), C&DW attracts significantly less attention than other forms of waste, such as municipal solid waste. C&DW, being both produced and managed mostly by the private sector, suffers from weak enforcement provisions. C&DW management practices which are dictated by economic incentives likewise have resulted in large scale landfill dumping practices, illegal dumping, and open burning. In the Begum, Siwar, Pereira, and Jaafar (2009) study, cost, lack of knowledge and awareness of waste recovery are the major hindrances against source separation and recycling. Malaysia's minimal level of C&DW recovery is also attributed to a scarcity of reliable C&DW data in fostering the growth of C&DW recycling facilities.

In the view of environmental economists, waste causes negative externalities to the environment, despite the fact that most of the CDW is inert materials (Franklin Associates, 1998b) and may not pose as great a threat as hazardous and municipal solid waste (J. Y. Wang, Touran, Christoforou, & Fadlalla, 2004). Nevertheless, C&DW depletes finite landfill resources (Marzouk & Azab, 2014), contributes to the increase of energy consumption, increases greenhouse gas (GHG) emissions, presents public health issues, and otherwise contaminates the environment. In the UK, the industry emits approximately 250.3 million tons CO_2 annually (BIS, 2010) and in the USA, it accounts for 39% of the country's total CO2 emissions, more than any other individual sector (USGBC, 2006).

The minimal level of recovery is also attributed to a scarcity of appropriate recycling and secondary market infrastructure. In areas with lower disposal costs, dumping will become a more economically sound option, whereas higher disposal costs in an area result in waste recovery becoming the preferable option (USEPA, 2003). For C&DW material that traditionally yields a high resale value (scrap metal), it will be recovered at the originating site, regardless of disposal fees, prior to the waste's complete removal from the site (Llatas, 2011). Eusuf et al. (2012) suggest that landfill dumping is the most common practice for discarding other types of C&DW material: concrete, reinforced concrete, drywall, rubble, roofing, and brick. On the other hand, plastic, paper, and cardboard are mainly recycled. According to the Franklin Associates (1998b) study, when there are available recycling facilities, the materials most frequently recovered and recycled are concrete, asphalt, metal, and wood, while plasterboard and asphalt shingles are recovered to a lesser degree for recycling.

Malaysia construction industry is lacking of awareness of recycling waste. Dumping is seen to be easiest and most efficient way to manage waste. The current practice on-site is to dump everything except reselling just scrap metal which values approximately about RM 500 – RM 1000 (USD 138 – 278) per ton. Waste generated on site manages by waste sub-contractor charging an average of RM 450 (~ USD 125) per truckload for dumping. Sub-contractor will then transport waste either to illegal dump site, to landfill, or some re-useable items (plywood, timber, and paper) will be resell (Mah & Fujiwara, 2015).

C&DW management hierarchy indicates the management order of preferences for minimizing waste material (Figure 2). The waste management hierarchy captures the progression of a waste material through the successive stages of waste management and represents the preferable end-of-life for the waste material life cycle. Waste management hierarchy aims to extract and utilize the material to the optimum scenario such as to maximize the economic value, to minimize the environmental impacts, to reduce the GHG emissions, to reduce pollutants, and to conserves natural resources.

Historically, waste material recovery has always been driven by the economics value. In places where the natural resources or dumping fees were high, recovery became economically viable. If in contrast, landfilling will become the preferable choice to manage C&DW.

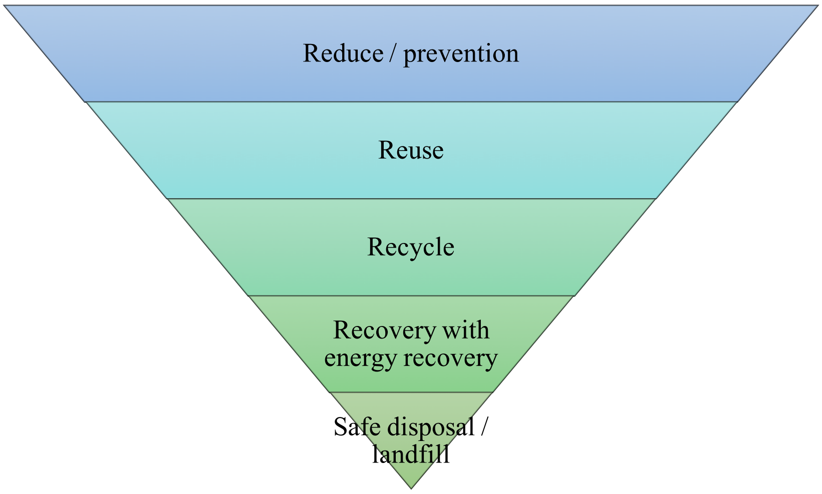

Figure 2: C&DW management hierarchy

Materials that traditionally yield a high value even in a used state, such as scrap metals, were recovered regardless of the disposal fees. The economic driver remains unchanged in Malaysian's construction industry, but with additional factors such as green building index (GBI) in influencing the likelihood of C&DW material being recover. In GBI, it gives additional points for on-site C&DW separation and recycling and since there are more construction projects in Malaysia are in involves in reusing and recycling C&DW materials.

The first in the hierarchy is source reduction or waste prevention. Source reduction in construction is a pre-construction activity that designed to reduces the material consumption throughout the life cycle. The activities in source reduction include value engineering to optimize the structural design or architectural features to minimize the material consumption, improvement in construction technology to increase efficiency, thus reducing waste generation. Other efforts include purchasing optimization to avoid surplus. The amount of C&DW materials avoided through these efforts has not been well documented and there are no known and reliable data benchmarking the reduction.

Although source reduction is the top priority in the waste management hierarchy, it is always not easily attainable. This followed by reuse of C&DW material as the second preferred choice. Reusing of C&DW material can be achieved by several methods included; designing a building that support adaptation, disassembly, and reuse of the C&DW materials. Materials like soil, sand, gravel, and aggregate can be reuse without reprocessing. Plywood for concrete casting is reusable up to a few cycles, depending of the wood material and after-use maintenance. At the end-of-life cycle, wood waste can be recycled into wood chip and utilized for bio energy production. After reduce, recycling or down-cycling of C&DW material is the next preferred option. Most of the C&DW materials fall into this option. Waste material like concrete rubble is often crushed, down-cycle it into road base material or recycled concrete aggregate (RCA) to replace natural aggregate.

The C&DW materials, if not too severely contaminated; almost all of it should be recovered and recycled. The major constituents of C&DW materials most frequently recovered and recycled are concrete / aggregate, reinforced concrete, scrap metal, wood, packaging, paper, board, and asphalt (not covered in this study). Wood and packaging, paper, and board, if recovered, can be incinerating for energy recovery. If these inert materials are not recycled, they are destined to landfill. Table 1 recorded the possibility of C&D waste materials recovery.

Table 1: Possibility of C&DW materials recovery

	Reduce	Reuse	Recycle	Burn / Incineration	Landfill
Brick					
Cement					
Concrete					
Gypsum					
Packaging paper board					
Reinforced concrete					
Sand soil dirt					
scrap metal					
Tiles					
Timber plywood					

Priority / Preferences

1

2

3

4

5

Prevent

2.2 Waste Generation Rates (WGR)

Over the past decade, rapid urbanization and insufficient attention to C&DW particularly in developing countries like Malaysia, have contributed to an urgent need for additional research on waste generation rate (WGR) (Begum, Siwar, Pereira, & Jaafar, 2007; J. Wang, Yuan, Kang, & Lu, 2010). To account for externalities and environmental costs, quantitative waste data is fundamentally important (Myers, 2017). Waste minimization and recycling are difficult to implement when quantitative data regarding waste composition and WGR are not reliably known (Hassan, Rahman, Chong, Zakaria, & Awang, 2000). Quantitative waste data provides measurable indicators to estimate WGR in a project, serving as a decision-making tool in planning for an efficient waste management plan, and are central to assessing the feasibility of waste recycling. Marzouk and Azab (2014) study suggested a savings of 12.3 million tons in raw materials substitution if recycling is conducted on the same quantity of landfill disposed material. In Australia, studies proved that effective waste management plan reduce waste generation by 15%, with 43% less waste sent to landfill, and savings of 50% on related waste handling costs (McDonald & Smithers, 1998).

Waste is generated throughout the entire construction period. Typically, C&DW is inert (Franklin Associates, 1998a). Complete and precise quantification of waste from the beginning to end is not economically practical for developers, and thus nearly impossible for a researcher. The industry does not usually store waste information unless there are monetary incentives to outweigh the costs of additional administration, delays, and the overall effects on the construction process' efficiency. Current economic incentives have not resulted in the gathering of any significant or detailed statistical data on C&DW generation by project developers.

A number of international researchers are aware of this C&DW situation and have devoted applicable research to the WGR. These researches (Franklin Associates, 1998b; Llatas, 2011; Lu et al., 2011; Poon, Yu, & Jaillon, 2004) focused on regional estimations that required large existing databases of information. In Malaysia, there is no official published, reliable C&DW data regarding to WGR or CDW material recovery. There do exist a few studies in Malaysia (Lachimpadi, Pereira, Taha, & Mokhtar, 2012; Lau, Whyte, & Law, 2008; Lee, Rahman, Asmi, Nagapan, & Khalid, 2013) that addressed the WGR based on the project basis and discussed the recyclability of C&DW material. In these studies, the researchers estimate WGR by using the methodology of onsite hand-sorting or machinery-based-sorting. This methodology is mainly known for costly and time-consuming, requiring a high degree of manpower and machinery, thus limiting the number of projects involve in the researches.

Table 2: Previous research on waste composition and generation rate

Author	Type of Project	Type of Waste (%)								WGR ($t/100m^2$)
		Concrete	Steel Metal	Brick	Plastic/ Packaging	Wood	Others	Soil & Sand	Tiles	
Lee Chin Foo (2013)	Residential	9	1	26	15	49	-	-	-	-
		6	4	16	25	49	-	-	-	-
Lau et.al (2008)	Residential	13	3	13.7	-	69.6	0.7	-	-	1.41
		20.7	2.5	9.1	-	64	3.7	-	-	0.86
		37	2	19	-	35	7	-	-	2.29
Lachimpadi et al. (2012)	Residential Conventional	60	2	3	2	17	-	15	1	4.80
	Residential - Mixed system	30	2	4	3	9	-	50	2	3.02
	Residential - IBS	14	1	2	5	2	-	75	1	1.55

Source: (Foo, Rahman, Asmi, Nagapan, & Khalid, 2013), (Lau et al., 2008)

The WGR refers to the estimated amount of waste created by a construction project, based on its floor area. WGR may be used as a measure of the efficiency of a certain project in managing C&D waste. A higher WGR indicates a less efficient project, generating more waste per square metre, while a lower WGR indicates a more efficient project, generating less waste per square metre (Lachimpadi et al., 2012). WGR may also be used to estimate the future impact of a new development project. WGR and waste usage efficiency can differ with varying attributes, including: construction method, type of project, design specification, project size, and construction techniques and technologies used in the project (Jaillon, Poon, & Chiang, 2009a). According to (Llatas, 2013), worker skill and training will most affect the quality of adoption and implementation of waste management planning as well as the technical quality of the project (Llatas, 2013). As each development project is unique, specific waste management practices are dictated by the most economically feasible method for a certain project's characteristics. Differing project characteristics have a bearing on waste management, including: location of project and distance from landfill, project cost structure, contractor company size, manager and worker education and awareness, local policies, and local regulatory enforcement (Begum et al., 2009).

There are several methods for estimating WGR or quantifying C&DW. Waste can be estimated either by waste generation quantity or by waste disposal quantity ((Franklin Associates, 1998a). C&DW can also be quantified based on secondary records of waste flow and waste disposal (Mahayuddin & Zaharuddin, 2013). Waste estimates may be quantified by volume of waste generated, waste material density, and floor area of construction or demolition project (Kourmpanis et al., 2008). Waste quantity or volume can be obtained by measuring waste truck trips and size of the waste bin (Poon et al., 2004). However, the quantification method must be modified in accordance to the limitations of data quality and availability (Mahayuddin & Zaharuddin, 2013). A universal waste quantification model can rarely be applied, as the nature of C&DW data is dependent upon the local economic conditions, weather, disasters, and local regulations, availability of technology, labour and resources (Franklin Associates, 1998a). Furthermore, WGR will differ greatly according to variation in the following parameters: construction method used in the project, type of project, project size, and others (Jaillon, Poon, & Chiang, 2009b; Kourmpanis et al., 2008).

2.3 Construction method in Influencing the amount of C&DW generated

The Malaysian construction industry is generally considered a late-adopter of relevant technologies, due to the association of new methods with new risk and cost. The majority of the construction in Malaysia is conducted according to the conventional construction method (CCM). The CCM utilizes building components that are constructed on-site through the processes of casting with timber and plywood and is regarded as time-consuming, costly, and highly dependent on labor. The labor-intensive nature is a likely influence on the amount of waste generated by the method. (Teo & Loosemore, 2001). The Industrial Building System (IBS) Roadmap, initiated in 2003 by the Malaysia Construction Industry Development Board, has fostered a slow transition from the CCM to the nonconventional or the IBS method. Transitional efforts are seen in adoption of the cast in-situ method. The case-in-situ method uses lightweight prefabricated formworks of steel or aluminum that are easily erected, dismantled and reused to replace the use of traditional timber and plywood formwork. It has the effect of reducing labor dependency, maximizing productivity, and shortening construction periods. The transition effort remains in its infancy, as most construction projects utilizing the cast-in-situ method will do so in combination with the CCM. In this study, such combination of both methods is referred to as the "mixed-construction method" (MCM). Due to the prevalence of CCM and MCM in Malaysian construction industry, this study examines projects of both types in influencing WGR.

The Industrialized Building System (IBS) is a fully prefabricated construction method that uses all standardized elements, prefabricated in a factory and assembled on-site. IBS produces floor slabs, walls, bathroom units, staircases, and ceilings. This method is known to save time, increase construction productivity, and reduce on-site workload, waste generation and labor dependency (Musa, Mohammad, Mahbub, & Yusof, 2014). As a result of its standardized nature, IBS produces uniformity in design that is often perceived to be aesthetically limiting. Despite first being introduced to Malaysia in 1964 by the Ministry of Housing and Local Government, IBS has not been very successfully implemented in the country. Only two IBS projects have been built: Jalan Pekeliling Flats was the first project; the second project was a 17-storey, 3699 units, and six block project in Penang. Researchers suggest that the adoption of IBS could reduce construction waste (Eusuf et al., 2012). At present, however, no development projects in the study area are using a total IBS approach.

References

Begum, R. A., Siwar, C., Pereira, J. J., & Jaafar, A. H. (2007). Implementation of waste management and minimisation in the construction industry of Malaysia. Resources, Conservation and Recycling, 51(1), 190-202.

BIS. (2010). Estimating the amount of CO2 emissions that the construction industry can influence. from Department for Business Innovation & Skills: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/31737/10-1316-estimating-co2-emissions-supporting-low-carbon-igt-report.pdf (accessed November 7, 2015)

Eurostat (2015) Waste Statistics. From European Union, Publications (Sept 2015):http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics (accessed 7 Dec 2015)

EU, E. U. (2011). Supporting Environmentally Sound Decisions for Construction and Demolition (C&D) Waste Management. from Italy: http://eplca.jrc.ec.europa.eu/uploads/waste-Guide-to-LCTLCA-for-C-D-waste-management-Final-ONLINE.pdf (accessed July 28, 2017)

Eusuf, M. A., Ibrahim, M., & Islam, R. (2012). The construction and demolition wastes in Klang Valley, Malaysia. Journal of the Malaysian Institude of Planners, X(2012), 99-124.

Duan, H., & Li, J. (2016). Construction and demolition waste management: China's lessons. Waste Management & Research, 34(5), 397-398.

Fauziah, S. H., & Agamuthu, P. (2003). Municipal solid waste management: a comparative study on selected landfill in Selangor. Proceedings of Environment 2003 Environmental Management and Sustainable Development for Better Future Growth., Penang, Malaysia. February 18 – 19, 2003 pp 434- 437, USM Publisher

Foo, L. C., Rahman, I. A., Asmi, A., Nagapan, S., & Khalid, K. I. (2013). Classification and Quantification of Construction Waste at Housing Project Site. Internation Journal of Zero Waste Generation, 1(1).

Franklin Associates, P. V., KS. (1998a). CHARACTERIZATION OF BUILDING-RELATED CONSTRUCTION AND DEMOLITION DEBRIS IN THE UNITED STATES. The U.S. Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste.

Llatas, C. (2011). A model for quantifying construction waste in projects according to the European waste list. Waste Management, 31(6), 1261-1276.

Lau, H. H., Whyte, A., & Law, P. L. (2008). Composition and Characteristics of Construction Waste Generated by Residential Housing Project. International Journal of Environmental Research, 2(3), 8.

Lee, C. F., Rahman, I. A., Asmi, A., Nagapan, S., & Khalid, K. I. (2013). Classification and Quantification of Construction Waste at Housing Project Site. International Journal of Zero Waste Generation, 1(1).

Lu, W., Yuan, H., Li, J., Hao, J. J. L., Mi, X., & Ding, Z. (2011). An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. Waste Management, 31(4), 680-687.

Mah, C. M., & Fujiwara, T. (2015). Survey of Construction Waste of High Rise Mixed-Use Development in Malaysia (京都大学環境衛生工学研究会 第 37 回シンポジウム講演論文集). 環境衛生工学研究 : 京都大学環境衛生工学研究会機関誌, 29(3), 23-26.

Mah, C. M., Fujiwara, T., & Ho, C. S. (2017). Concrete Waste Management Decision Analysis Based On Life Cycle Assessment. Chemical Engineering Transactions, 56.

Marzouk, M., & Azab, S. (2014). Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. Resources, Conservation and Recycling, 82(Supplement C), 41-49.

MLIT. (2014). White Paper on Land, Infrastructure, Transport and Tourism in Japan 2014. Japan: Ministry of Land Infrastructure Transport and Tourism, MLIT Retrieved from http://www.mlit.go.jp/common/001063075.pdf (accessed 01.10.2016)

Myers, D. (2017). Construction Economics - a new approach (4th ed.). London and New York: Routledge - Taylor & Francis Group

NEA. (2016). Waste statistics and overall recycling. Singapore: National environment agency Retrieved from http://www.nea.gov.sg/energy-waste/waste-management/waste-statistics-and-overall-recycling (accessed May 24, 2017)

Poon, C. S., Yu, A. T. W., & Jaillon, L. (2004). Reducing building waste at construction sites in Hong Kong. Construction Management and Economics, 22(5), 461-470.

Poon, C. S., & Chan, D. (2007). The use of recycled aggregate in concrete in Hong Kong. Resources, Conservation and Recycling, 50(3), 293-305.

Sealey, B. J., Phillips, P. S., & Hill, G. J. (2001). Waste management issues for the UK ready-mixed concrete industry. Resources, Conservation and Recycling, 32(3–4), 321-331.

UNCRD. (2015). 3R as an economic industry - next generation 3r solutions for a resource efficient society and sustainable tourism development in asia and the pacific. Paper presented at the Sixth Regional 3R Forum in Asia and the Pacific, Malé, Maldives, 9-10,United nations centre for regional development

USEPA. (2003). Building related construction and demolition materials amounts.

USEPA. (2016a). Construction and Demolition Materials. USA: USEPA Retrieved from https://www.epa.gov/sites/production/files/2016-03/documents/warm_v14_construction_demolition_materials.pdf (accessed 01.09.2016)

3 Waste Generation Rates Estimation

3.1 Introduction

In recent years, due to the rapid urban growth and increase in land prices in the urban area, Malaysia's cities have seen a surge in high-rise mixed-use development (HRMUD). HRMUD comprises a combination of residential units, commercial spaces, and multi-story parking area, offers notable living conveniences and has become the new urban growth development paradigm. In Malaysia, despite the land prices, HRMUD is still developing on green field land, either new land or agriculture land. Demolition projects are uncommon in Malaysia, comprising only 0.1% of the total value of construction work done, whereas new construction projects comprise 64.4% (Department of Statistic, 2012-2015).

CDW of HRMUD is generated throughout the entire construction period (24 – 48 months) and the industry does not store waste information without monetary incentives to outweigh the costs of such additional administration, delays, and other effects on the business efficiency. Consequently, complete and precise WGR quantification is not economically practicable for builders, and thus nearly impossible for researcher to obtain such comprehensive data in Malaysia.

The primary purpose of this study is to propose a less burdensome and more broadly applicable alternative to estimate the WGR of construction and demolition projects in Malaysia. Given that HRMUD is still new and lacking in applicable WGR research, this study focuses on investigating the WGR of HRMUD, relative to the construction method employed. This study also investigates the composition of such CDW to identify the percentage of recyclable material.

A total of 11 projects were selected as case study; 10 construction projects and 1 demolition project. Of the 10 construction projects, there are 6 CCM projects and 4 MCM projects. No demolition waste was derived from existing structures on these 10 projects, as they were the green field development. This research limits its study to one demolition project due to the rarity of such type of projects in HRMUD, Malaysia. The demolition project was the partial demolition of previously abandoned development, and was the only one that fulfilled the project selection parameters stated below.

The projects were selected in accordance with the fulfilment of the following parameters:

- Project job-site accessibility;
- Project with available secondary data, such as invoices or reports on waste disposal trips or other waste costs; and
- Project where a waste sub-contractor handles the construction and demolition waste.

The 11 projects selected span a range of project scales comprising small, medium, and large projects; 2 projects with floor area (FA) exceeding 150,000 m2, 2 projects between 100,000 m2 and 150,000 m2, 4 projects between 50,000 m2 and 100,000 m2, and 2 projects with FA less than 50,000 m2.

3.2 Methodology and Data Collection

For the reasons mentioned above and to ensure a broader sampling, this study employs the method suggested in Poon et al. (2004), whereby waste generation is estimated as a function of the number of waste truck trips and the size (volume) of the waste bin being sent out of project site. The estimation of the total number of waste truck trips is illustrates in equation (1), with N is the total number of waste truck trips, Call is the total waste disposal cost, and C is the disposal cost per truck trip.

$$N = \frac{C_{all}}{C} \tag{1}$$

By doing on-site measurement, waste truck bin sizes are collected. Then, the volume of waste being disposed out of site is estimated with equation (2), with Vall is the total waste disposal volume and V is the size of the waste bin.

$$V_{all} = V \times N \tag{2}$$

With the modification in accordance to Malaysian construction industry, WGR is estimated through the indicative mathematical model used by Fatta et al. (2003) and Kourmpanis et al. (2008). WGR of waste category k is defined by equations (3).

$$WGR\ (k) = \frac{[\boldsymbol{total\ waste\ disposed\ (m^3)}] \times [\boldsymbol{waste\ (k)\ composition}\ (\%)] \times [\boldsymbol{waste\ (k)\ density\ (t\ m^{-3})}]}{\boldsymbol{Floor\ area\ (m^2)}}$$

$$= \frac{\boldsymbol{V_{all} \times Com(k) \times \rho(k)}}{\boldsymbol{FA}}$$

Where FA is the floor area constructed or demolished (m^2), ρ(k) is the waste k density (t m-3), Com(k) is the waste (k) composition (%) that is collected through interviews and review of reports.

The WGR estimation is rendered subject to the following assumptions:

- All waste generated on-site is transported by waste truck with a waste bin.
- The waste bin is fully loaded when it is transported out of site.
- No domestic waste in the waste bin (domestic waste is usually disposed separately).
- Total input of timber and plywood is equal to total output, regardless of recycling path.
- No burning of timber and plywood is conducted on-site.
- Plastic, paper, and cardboard are recycled and not part of the waste disposal output.
- No consideration is given to the waste generated on-site that is reused or recycled back on-site.

Data collection is accomplished through the following methods:

- Review of existing secondary data, including monthly progress report, waste management plan, contractor claims and invoices, bill of quantities and tender documents indicating waste disposal cost, waste composition, and frequency of disposal;

- Gathering of primary empirical data through periodic site observations conducted throughout the first half of 2015, including sampling and measurement of waste bin size; and
- Structured interviews and surveys of related personnel, to supplement and qualitatively improve the above-referenced primary and secondary data obtained.

Waste material density (ρ) is obtained from the average of data gathered from Australia, New Zealand, and Japan (Table 3). With the lack of directly applicable, published CDW data from Malaysia, the average density data provides a reliable, if general, estimate. Due to waste materials varying in shape and packed volume, total waste amounts are generally described in weight.

Table 3: Waste material density

Waste Composition	Density $\rho(k)$ ($t\ m^{-3}$)
Concrete/ Aggregate	1.26
Cement/ Plaster	0.92
Reinforced concrete	1.44
Dirt/ Soil/ Sand	1.56
Timber/ Plywood	0.39
Brick/ Block	1.40
Scrap metal	0.90
Tile	1.17
Plasterboard	0.33

Sources: ((Burton & Friedrich, 2008; JIWIC, 2015; NAHB, 1997)

3.3 Results and Analysis

3.3.1 Waste Composition

Table 4 illustrates the basic numerical data of the 11 projects and is uses as the basis for the WGR estimation. Projects 1-6 follow the CCM. Projects 7-10 utilize the MCM. Project 11 is a demolition project.

Table 4: Project information and waste composition

Project		Conventional construction method						Mixed-construction method				Demolition
		1	2	3	4	5	6	7	8	9	10	11
Waste (m^3)		2148	12969	18396	5500	9764	7776	4792	2097	4296	2610	135790
Floor Area (m^2)		17300	96405	182827	61006	91029	86897	217279	68670	119259	45583	128985
Disposal cost (RM)		60000	156000	300000	167440	200000	85800	234450	76950	128000	140940	487590
Waste Composition	Concrete/ Aggregate	19	22	18	12	15	15	13	25	25	15	16
	Cement/ Plaster	15	5	11	12	20	20	17	7	5	15	10
	Reinforced concrete	12	12	8	5	15	15	13	10	15	10	-
	Sand/ Soil	1	-	20	10	1	2	-	10	20	30	-
	Timber/ Plywood	30	40	30	45	25	25	30	20	10	10	-
	Brick/ Block	4	3	5	5	8	3	6	10	10	7	6
	Scrap metal	12	12	2	3	10	14	14	3	2	3	68
	Tile	5	5	3	5	4	5	7	10	8	5	-
	Gypsum	2	1	3	3	2	1	-	5	5	5	-
Total (%)		100	100	100	100	100	100	100	100	100	100	100

Table 5 shows the estimation of waste composition by weight. CDW composition information allows developers to strategically act regarding storage planning, waste material trading opportunity, and waste separation. Total waste generation by the 6 CCM projects is estimated at 52,718 tons, with an average of 8,786 tons per project. While the 4 MCM projects produce a total of 14,813 tons, with an average of 3,703 tons per project. Total waste generated by a demolition project is estimated at 134,508 tons.

Table 5: Waste composition for projects

Project	Conventional construction method								Mixed-construction method						Demolition		
	1	2	3	4	5	6	Total	*Comp	7	8	9	10	Total	*Comp	11	Total	*Comp
Concrete/ Aggregate	513	3,584	4,158	829	1,840	1,465	12,389	24	782	658	1,349	492	3,282	22.2	27,288	27,288	20
Cement/ Plaster	297	598	2,327	609	1,800	1,434	7,065	13	751	135	198	361	1,445	9.8	12,520	12,520	9
Reinforced concrete	370	2,235	2,113	395	2,103	1,675	8,891	17	895	301	925	375	2,496	16.8	-	-	-
Sand/Soil	34	0	5,751	860	153	243	7,041	13	0	328	1,343	1,224	2,895	19.5	-	-	-
Timber/ Plywood	251	2,023	1,655	965	952	758	6,606	13	561	164	168	102	994	6.7	-	-	-
Brick/ Block	120	543	1,039	384	1,090	325	3,501	7	401	293	599	255	1,548	10.4	11,366	11,366	8
Scrap metal	233	1,405	423	149	881	982	4,073	8	605	57	78	71	810	5.5	83,334	83,334	62
Tiles	126	759	645	322	457	455	2,764	5	392	245	402	153	1,193	8.1	-	-	-
Gypsum	14	43	184	55	65	26	389	1	0	35	72	44	151	1.0	-	-	-
Total (t)	1,957	11,189	18,300	4,567	9,341	7,364	52,718	100%	4,388	2,216	5,134	3,075	14,813	100.0%	134,508	134,508	100%

*Comp = composition

Figure 3 illustrates the waste composition resulting from the CCM projects. The concrete/aggregate category represents the highest percentage (24%) of the waste sampled, followed by reinforced concrete (17%). Cement/plaster, sand/soil, and timber/plywood each represent approximately 13% of the waste.

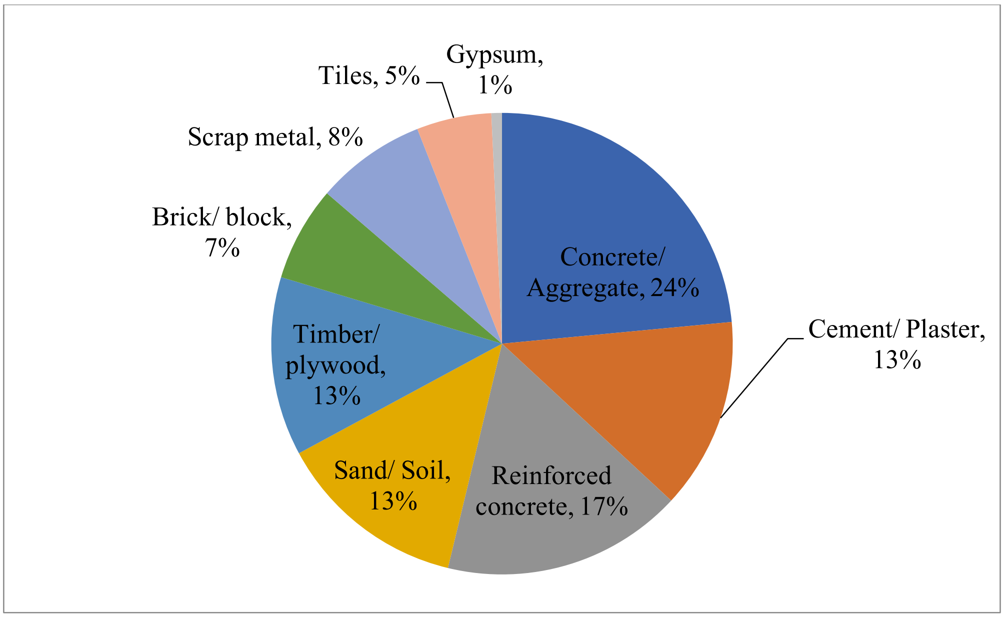

Figure 3: CCM waste composition (t)

Concrete, aggregate, reinforced concrete, and cement are the main materials in building construction. Project contractors often do not know the exact quantity of each material required, relying instead on estimation that is prone to waste of concrete. Concrete production is time-sensitive and must match up with daily work demand, with a tendency to oversupply rather than risk a costly work delay. In HRMUD concrete is pumped by hose in a liquid state, tending to waste more concrete the higher the floor of construction.

The CCM relies mainly on timber/plywood as the temporary formwork for casting of building structure. The high timber/plywood composition of the waste is correlated to the formwork, which is discarded regardless of its reusability cycle. The interview survey revealed that contractors are inclined to most inexpensively dispose of timber/plywood by on-site burning. Accordingly, the actual amount of wood waste may exceed 13% of total project waste. Tiles and gypsum are generated only at the construction finishing phase, being strongly affected by the handling skill, design, and material quality. While gypsum board is often used for ceilings in commercial developments, builders wishing to reduce costs do not often use this material for HRMUD, thus the lower percentage of waste.

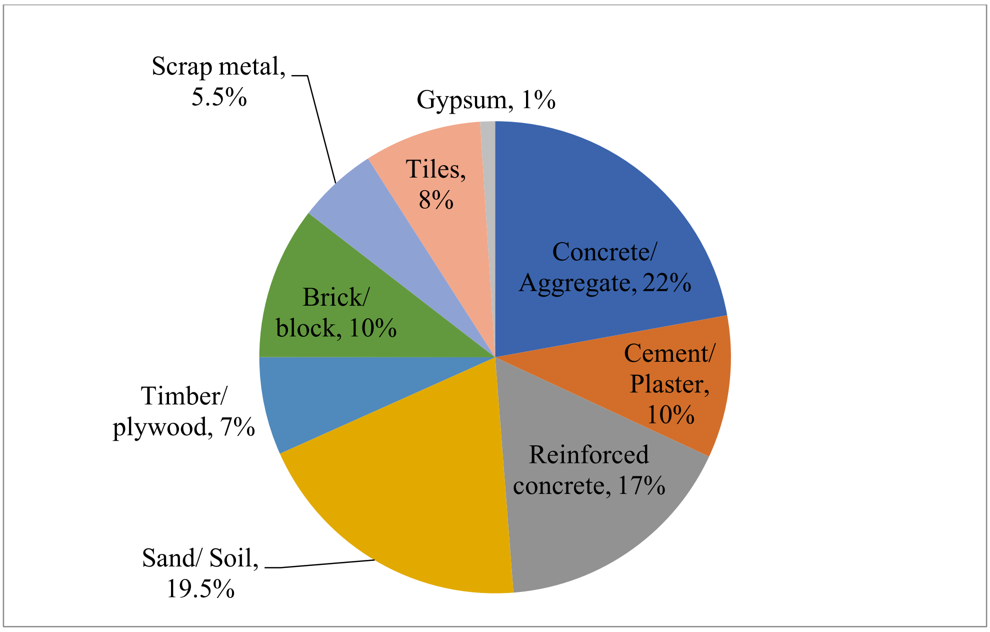

Figure 4: MCM waste composition (t)

Figure 4 shows the waste composition of the MCM projects. Concrete/aggregate (22%), reinforced concrete (17%), and cement/plaster (10%) still represent the largest category, and 49% of total waste. Timber/plywood waste is substantially lower in the MCM projects. Cast in-situ system formwork (steel or aluminium) used in MCM projects account for the reduction in timber/plywood, concrete/aggregate, and cement/plaster waste. System formwork is only feasible by the economies of scale, when the building's design is repetitive enough to justify the initial formwork moulding design costs. In MCM projects, system formwork is used in casting of main floors, beams, and columns, but wood is still used for casting internal walls and various differing design features.

Sand/soil occupies a larger percentage (19.5%) of total waste, reflecting the greater impact of excavation work done in the earlier construction stages.

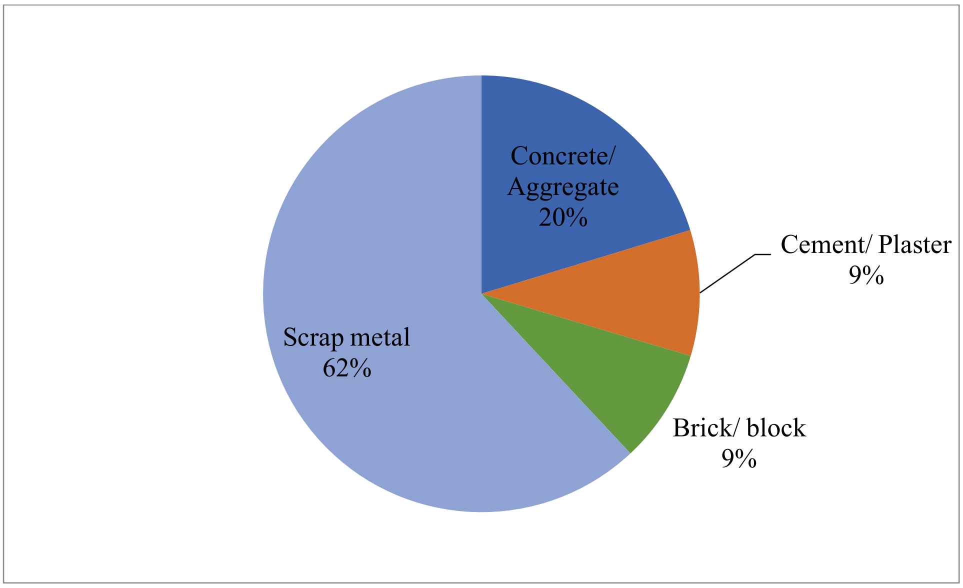

Figure 5: Demolition waste composition

Figure 5 shows that demolition waste is mainly composed of scrap metal, concrete/aggregate, brick/block, and cement/plaster. The demolition case study waste composition reflects that it was a building project abandoned at the structural stage, resulting in no waste from internal finishes. The demolition project adopted partial selective demolition method, facilitating on-site waste separation. Crushing machines were utilised to separate metal bars from concrete and aggregate, producing a large amount of scrap metal, accounting for 62% of the total waste sampled. Scrap metal is most readily recyclable, possessing a high secondary market value, which is applied to offset the contractor costs. The remaining 38% of project waste was not recycled and was instead sent to a dump site.

3.3.2 Waste generation rate

Results show that the different construction methods generate waste at different rates (Table 6). WGR is a useful performance measure in managing waste across a spectrum of project sizes. A higher WGR indicates a less efficient project, generating higher waste per square meter, and vice-versa. On average, the WGR for CCM is estimated at 9.85 t $100m^{-2}$, while the WGR for MCM is estimated at 3.29 t $100m^{-2}$.

Table 6: WGR and disposal cost

Project		Waste	Floor Area (FA)	WGR	Waste disposal cost	Disposal cost per floor area
		(t)	(m^2)	(t /$100m^{-2}$)	(RM)	(RM m^{-2})
Conventional construction method	1	1,957	17,300	11.31	60,000	3.47
	2	11,189	96,405	11.61	156,000	1.62
	3	18,300	182,827	10.01	300,000	1.64
	4	4,567	61,006	7.49	167,440	2.74
	5	9,341	91,029	10.26	200,000	2.20
	6	7,364	86,897	8.47	85,800	0.99
	Average	52,718	535,464	9.85	969,240	1.81
Mixed-construction method	7	4,388	217,279	2.02	234,450	1.08
	8	2,216	68,670	3.23	76,950	1.12
	9	5,134	119,259	4.30	128,000	1.07
	10	3,075	45,583	6.75	140,940	3.09
	Average	14,813	450,791	3.29	580,340	1.29
Demolition	11	134,508	128,985	104.28	487,590	3.78

This study finds that the CCM generates more waste per square meter than the MCM, and appears to be less efficient. Even though this study does not provide research on purely IBS project, the WGRs estimated may still serve as a useful indicator to the WGR reduction benefits of adopting such construction method. In the Lachimpadi et al. (2012) study, the CCM was found to generate waste at 4.56 t $100m^{-2}$, and the MCM at 3.02 t

100m^{-2}. Although the WGRs of both studies are not quite similar, the WGRs from both studies displayed a similar upward pattern that suggests WGR of the CCM is greater than the WGR of the MCM. The most waste is generated from the demolition project, with a WGR of 104.28 t 100m^{-2} (Table 6).

C&DW material that traditionally yields a high resale value, such as scrap metal, will be recovered at the originating site, regardless of disposal fees (Llatas, 2011). Landfill dumping is the most common practice for discarding other types of C&DW material, such as concrete, reinforced concrete, drywall, rubble, roofing, and brick. Accounting for all of the projects studied, a total of 56% or 113,821 tons of waste is disposed to landfill while a total of 88,218 tons or 44% of scrap metal is recycled. Scrap metal resale prices could vary on global market price and the volume submitted to the recycler. Scrap metal resale value (approximately RM600 per ton) is estimated to be around 30-40% of the current new material price (RM2000 per ton), possibly yielding up to RM52 million in resale value across the projects.

This study also collected waste disposal cost data to better relate the WGR to waste management policies. The average disposal cost is RM1.81 m^{-2} for the CCM projects and RM1.29 m^{-2} for the MCM projects. Disposal cost tends to be higher when the WGR is higher. For demolition project, the average disposal cost is estimated at RM3.78 m^{-2} for all (100%) waste. However, accounting for the 62% of scrap metal recycled, the disposal cost for material that is not readily recyclable material (concrete/aggregate, cement/plaster, and brick/block) is further reduced to RM1.44 m^{-2}. Reduction in disposal costs illustrate the benefit of recycling C&DW, which (while not entirely absent) is muted in practice by the lack of incentives, enforcement, and supporting infrastructure for builders.

3.4 Summary and Conclusion

The theoretical method presented in this study demonstrates a less burdensome framework for waste generation rate (WGR) estimation through available secondary data input, interviews with site personnel, and periodic site observation. Such method is significantly more practicable than the costly on-site hand sorting or machinery-sorting method. The findings from this study also demonstrate the role of the construction method in influencing WGR, highlighting the benefits of transitioning from the conventional construction method (CCM) to the mixed-construction method (MCM), particularly in respect to reducing WGR on-site.

WGR data obtained through this method may be applied to a broader series of case studies, and may serve as the foundation for a regional C&DW database and C&DW projections. With pending massive increases in Malaysian housing demand, and the revival of previously abandoned projects, the opportunity for utilizing such regional WGR data is clear, especially where such data suggests the potential for future growth in the C&DW recycling industry. Where there are available recycling facilities, the economics may shift to justify an increase in recycling C&DW.

Building a quantitative WGR database is crucial in measuring the economic and environmental costs of C&DW. Informed consideration of WGR database information may empower stakeholders and government agencies to meaningfully address the business and environmental impact of C&DW. Policy makers may benefit from a WGR database in developing appropriate policies to C&DW management, planning for cost associated with landfill management, pricing of dumping fees, and assessing the feasibility of C&DW recycling facilities.

It should be noted that the waste density data employed in this study was a composite figure sourced from many countries, and is most usefully understood as an approximation. To improve the accuracy of the WGR, the authors suggest utilizing the waste density data from the same country and region, where available. Due to variation across projects, additional studies on waste composition are needed to refine the accuracy of this research result. WGR established from this study cannot be validated for exact accuracy, and represents one important project type, rather than the industry as a whole. Nevertheless, this study and associated methodology may be useful as an expedient, economical decision-making tool for stakeholders.

References

Burton, E., & Friedrich, N. (2008). Net waste tool - guide to reference data. from http://nwtool.wrap.org.uk/Documents/WRAP%20NW%20Tool%20Data%20Report.pdf (accessed December 3, 2015)

Department of Statistic, M. (2012-2015). Quarterly construction statistics. Department of Statistics Malaysia Retrieved from https://newss.statistics.gov.my/newss-portalx/ep/epProductFreeDownloadSearch.seam (accessed December 20, 2015)

Fatta, D., Papadopoulos, A., Avramikos, E., et al. (2003). Generation and management of construction and demolition waste in Greece—an existing challenge. Resources, Conservation and Recycling, 40(1), 81-91.

JIWIC. (2015). Weight conversion coefficient of industrial waste (in Japanese). Retrieved from http://www.jwnet.or.jp/jwnet/pdf/gyouseihoukoku_jyuuryoukanzankeisuu.pdf (accessed December 24, 2015)

Kourmpanis, B., Papadopoulos, A., Moustakas, K., Stylianou, M., Haralambous, K. J., & Loizidou, M. (2008). Preliminary study for the management of construction and demolition waste. Waste Management & Research, 26(3), 267-275.

Llatas, C. (2011). A model for quantifying construction waste in projects according to the European waste list. Waste Management, 31(6), 1261-1276.

Poon, C. S., Yu, A. T. W., & Jaillon, L. (2004). Reducing building waste at construction sites in Hong Kong. Construction Management and Economics, 22(5), 461-470.

4 Estimation of Average Waste Generation Rate in 2025

4.1 Introduction

The purpose of this chapter is to estimate the total C&DW generated and its composition in the next future 10 years with using the data collected and analyzed in Chapter 3 to extrapolate to year 2025. The focus of this chapter is on C&DW related waste from high rise residential development, excluded infrastructure, road, bridge, and nonresidential development.

4.2 Methodologies to Estimate Waste Generation in 2025

The methodology use in this chapter to extrapolate the WGR and total C&DW generated in 2025 based on the average WGR data collected from 11 C&D projects in Malaysia. This method is known as point source waste assessment data with waste sampling and estimating at a variety of project sites to estimate the amount of high rise residential building-related C&DW produced nationally.

This method is employed in Franklin Associates (1998b) report in characterizing the building-related C&DW in the US. Although this method is known to be a basic and general method in estimating, accurate record of the precise amount of C&DW generated, if any, could modified the accuracy of the estimation accordingly. In Malaysia, there is no known record of C&DW generated, thus employing this method in this study is expected to be the trend setter towards better characterization and recording of C&DW generated, nationally.

The method begins with projection of the construction industry growth to estimate the total area needed and the total area that will be built in 2025 to cater for the: economic growth and population growth in Malaysia (Figure 6).

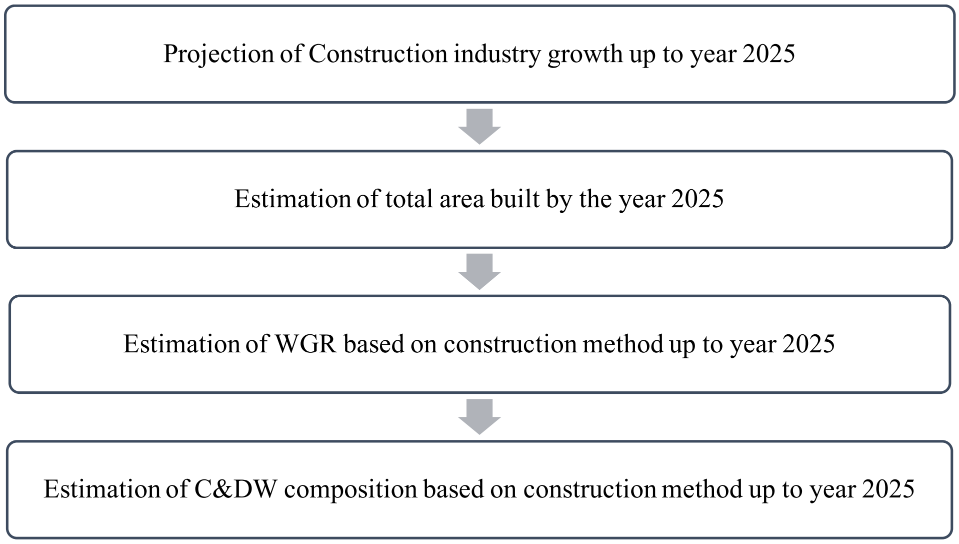

Figure 6: Methodology used in C&DW estimation up to year 2025

4.3 Estimation of Average Waste Generation Rate

For the estimation of C&DW generation up to year 2025, this study adopts previous research result and use the average waste composition for the estimation study. Due to limited research on C&DW conducted in the region, this study adopts one of the study results in Lachimpadi et al. (2012) research to calculate the average WGR (Table 7).

Table 7: Waste generation rate by construction method

Construction method	t / 100 m^2
Conventional	9.88
Mixed	3.29
IBS	1.55
Demolition	104.28

Waste generation rate for IBS method is adopted from Lachimpadi et al. (2012) study.

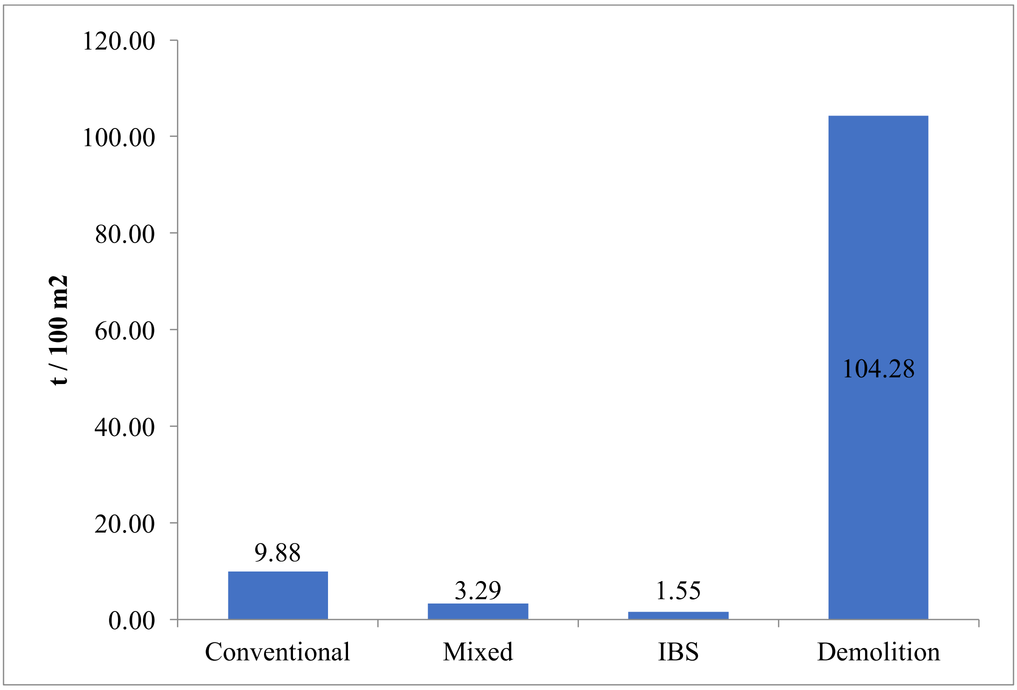

Figure 7: Waste generation rate by construction method

Waste generation rates differ by different construction method. Conventional construction method generates average 7.34 t /100m^2, mixed construction method at average 3.16 t /100m^2, IBS is the lowest at 1.55 t /100m^2. Demolition project is generating 104.28 t /100m^2 (Figure 7).

4.4 Projection of Construction Industry Growth up to year 2025

The Malaysian construction industry registered and average annual growth rate at 10.7% from year 2011 – 2015. The growth is supported by the 10th Malaysia Plan 2011 – 2015 which supported the investment growth in infrastructure, industrial parks, and residential buildings. According to the Department of Statistics Malaysia (DOSM) data (table above), the total construction value of high-rise residential construction work increased by 10 % from MYR 30.5 billion in 2014 to MYR 33.8 billion in 2015. The precedent year's growth rates were recorded at 18 %, 16 %, 23 % and 23 % in 2014, 2013, 2012, and 2011 respectively. Construction industry development board (CIDB) Malaysia sees 8 % growth in 2017 (Department of Statistic, 2015).

Malaysia is expected to keep growing in it economy and with the aim to become a developed nation by year 2020, accelerating growth is the main path for Malaysia to achieve convergence in developed nation economics. The Malaysian construction industry's growth is fundamentally driven by 11th (2016 – 2020) and the future 12th Malaysia plan (2021 – 2025). A few initiatives highlighted by the government in 11th Malaysia Plan are the development of national transportation infrastructure that will help in spurring new development and the government's initiative to provide affordable housing to all Malaysian. The government announced plan to build 175,000 units of affordable houses and 300, 000 units of low cost houses across the country by 2020. The government also pledges to reduce national greenhouse gas emission by 40 % in 2020. Consequently, Malaysia plans to increase the renewable energy resources in the country's energy profile. For instant, to build 1,250 solar power plant and a biomass plant by 2020.

On how to predict the growth accurately, it needs to consider the real factors that allow the country to create new wealth, which is beyond the scope of this study area. Thus, the growth rate predicted in this study is an extrapolation on a time-series growth based on the positive historical growth trend (figure 8).

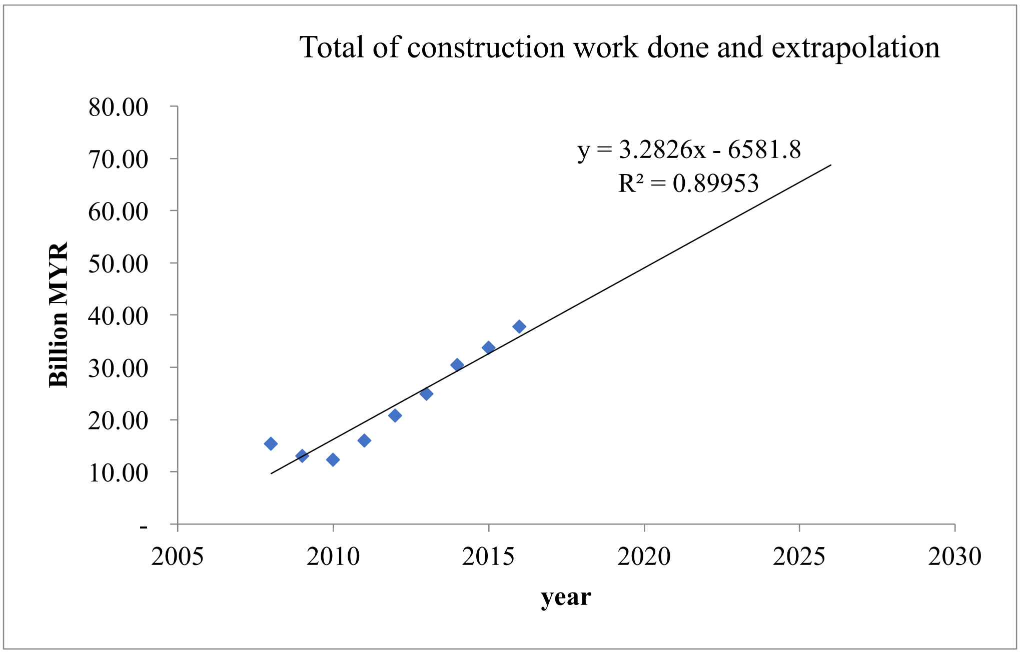

Figure 8: Extrapolation of high-rise residential construction growth up to year 2025

4.5 Estimation of Total Area Built by Year 2025

Although these costs do not have direct relationship with construction materials consumption as they may include inflation, material price fluctuation, profits, and other costs. However, they can be used as an indicator of construction activity.

The amount of C&DW materials is dependent on the amount of activities that take places in the entire construction industry. Construction industry is a vital sector of the nation economy growth, directly or indirectly, in providing housing, creates job, and income to the growing population. As such, construction industry growth is usually viewed as an indicator of the economy growth.

In between 2008 – 2016, the total value of residential construction work done had increased 144.5 %. During the same period, the population of Malaysia only increased 22 % (Department of Statistic, 2016).

Table 8: Estimation of total area built by year 2025

Year	Value of high-rise residential construction work done * MYR (billion)	Total changes %	Cost of construction ** MYR/m^2	Total area built *** m^2
2008	15.46			
2009	13.10	(6.03)		
2010	12.31	30.45		
2011	16.06	29.97		
2012	20.87	19.62		
2013	24.96	22.24		
2014	30.52	10.91		
2015	33.85	11.70	1,963	17,241,977
2016	37.81	3.64	2,022	18,698,841
2017	39.18	8.38	2,101	18,651,585
2018	42.46	7.73	2,172	19,549,492
2019	45.75	7.18	2,248	20,348,503
2020	49.03	6.70	2,327	21,071,118
2021	52.31	6.27	2,408	21,721,592
2022	55.60	5.90	2,493	22,303,976
2023	58.88	5.58	2,580	22,822,132
2024	62.16	5.28	2,670	23,279,738
2025	65.44		2,764	23,680,297

* The value of residential construction from Department of Statistic (DOS) Malaysia

** The construction cost is fromJuru Ukur Bina Malaysia (JUBM) - apartment, high rise (Bina, 2017)

MYR 1963 is derived from the average highest and lowest price of average standard and luxury standard apartments, high rise in Kuala Lumpur (1025+2900)

*** The calculation or total area built included 3% of Malaysia 2016 inflation rate, 3.9% in 2017, 3.4% in 2018, 3.5% in 2019, 4.1% in 2020, and a fixed average inflation rate of 3.5 % from 2020 – 2025.

Malaysia inflation rate forecast is obtained from tradingeconomics.com. Due to uncertainties in future inflation rate, this study uses the average value which subject to changes.

Total of area built in 2016 is estimated by using dividing the value of residential construction work done in 2016 with cost of construction in 2016.

$$Total\ area\ built\ in\ 2016 = \frac{value\ of\ residential\ construction\ work\ done\ in\ 2016}{Cost\ of\ construction\ in\ 2016}$$

$$Total\ area\ built\ in\ 2016 = \frac{37{,}807{,}000{,}000\ (MYR)}{2{,}022 (MYR)}$$ = 18,698,841 m2

Extrapolation to the year 2025 estimated that the total value of residential construction work done in 2025 is around 65.44 million. The estimation of cost of construction in 2025 is drawn on a 3.5 % average inflation rate. By using the same method, the projected total residential area built in 2025 is 23.68 million m^2 (Table 8).

$$Total\ area\ built\ in\ 2025 = \frac{value\ of\ residential\ construction\ work\ done\ in\ 2025}{Cost\ of\ construction\ in\ 2025}$$

$$Total\ area\ built\ in\ 2025 = \frac{65{,}440{,}000{,}000\ (MYR)}{2{,}764\ (MYR)}$$ = 23,680,297 m^2

4.6 Estimation of Waste Generation Rate up to Year 2025

The estimation of C&DW total waste generation is estimated by dividing the total area built with the average waste generation rate from Chapter 2. Table 8 recorded the estimated C&DW generation based on different construction method and the data are recorded up to the year of 2025.

$$Total\ C\&DW\ generation\ in\ 2016$$
$$= total\ of\ area\ built\ in\ 2016 \times waste\ generation\ rate$$

$$Total\ C\&DW\ generation\ in\ 2016 = 18{,}698{,}841\ m^2 \times 0.0988\ t/m^2 = 1{,}847{,}446\ \text{t}$$

Table 9: C&DW generation up to 2025

Year	Conventional (t)	Mixed (t)	IBS (t)
2016	1,847,446	615,192	289,832
2017	1,842,777	613,637	289,100
2018	1,931,490	643,178	303,017
2019	2,010,432	669,466	315,402
2020	2,081,826	693,240	326,602
2021	2,146,093	714,640	336,685
2022	2,203,633	733,801	345,712
2023	2,254,827	750,848	353,743
2024	2,300,038	765,903	360,836
2025	2,339,613	779,082	367,045

The projection of total waste generation in 2025 shows an upward increment of 21 % from 1.85 million t to 2.34 million tons of C&DW (Figure 9). With the shift of construction method, the upward trend could be change from positive increment to positive reduction. The dotted lines in figure 5 shows the possibility of reducing 67 % (1.56 million tons reduction) of C&DW materials from conventional method to mixed construction method and 84 % (1.97 million t) from conventional to total IBS method (Table 10).

Table 10: C&DW generation in 2025

Year	Conventional	shift to mixed method	shift to IBS method
2016	1,847,446		
2025	2,339,613	779,082	367,045
Difference (t)	492,168	(1,068,364)	(1,480,401)
(%)	27%	-58%	-80%

Negative value indicates saving in total waste generation. Shifting from conventional construction method to mixed construction method could save 58% of overall waste generation. While shifting to IBS method could reduce approximately 80% of total waste generation (Table 10).

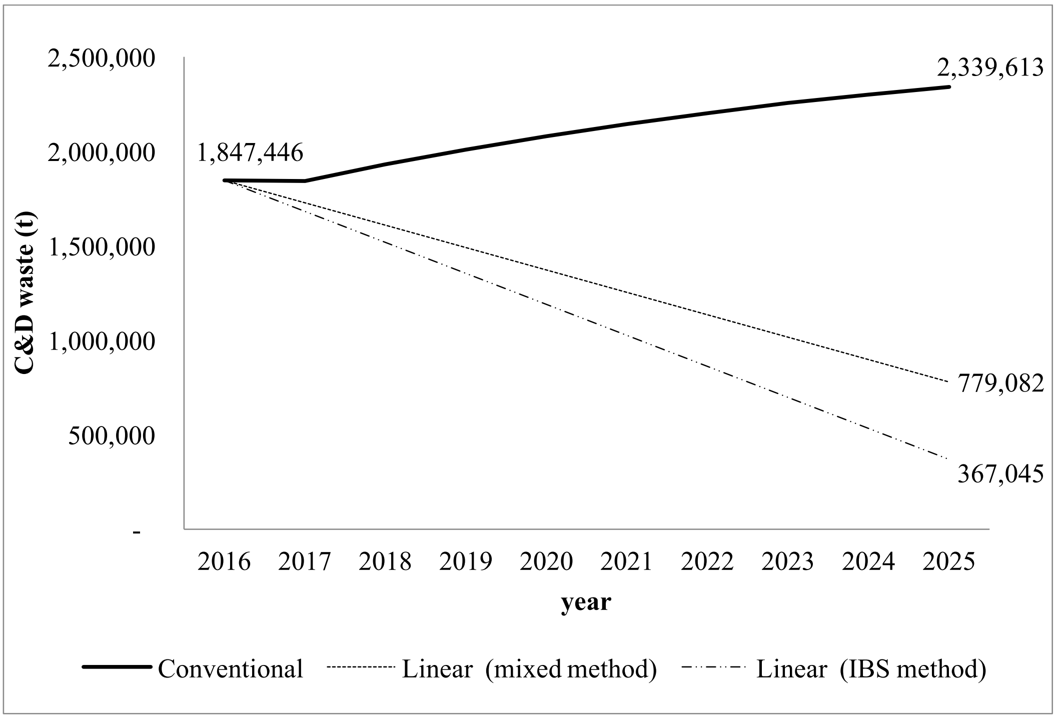

Figure 9: Reduction of C&DW from shifting to mixed construction method and IBS construction methods by 2025.

Another possibility if to consider the ratio mixed in employing construction method. Table 11 shows the possibility of reducing the C&DW generation by shifting from the conventional construction method to a ratio mixed of 5:3:2 (conventional: mixed: IBS). Instead of 21 % increment to year 2025, shifting to total mixed construction method could reduce 23 % (173, 182 t) of total waste generation by 2025 and 151 % (554, 434 t) for shifting to total IBS construction method (Table 11).

Table 11: Total waste generation in 2016 by construction method

Construction method	Total area built (m2)	CIDB IBS	Total area built (m2)	Average WGR (t /m2)	Total waste generated (t)
Conventional		50%	9,349,421	0.0734	686,247
Mixed	18,698,841	30%	5,609,652	0.03155	176,985
IBS		20%	3,739,768	0.0155	57,966
Total			18,698,841		921,198

4.7 Estimation of Waste Composition in 2025

The C&D waste composition from site survey and interviews.

Table 12: Waste composition by construction method

Waste type (%)	Conventional	Mixed	IBS
Brick	7	9	2
Cement	12	10	-
Concrete	23	22	14
Gypsum	1	1	-
Packaging paper board	1	1	5
Reinforced concrete	17	17	-
Sand soil dirt	13	19.5	75
Scrap metal	8	5.5	1
Tiles	5	8	1
Timber plywood	13	7	2
	100	100	100

Waste composition for IBS construction method is adopted from Lachimpadi (2013) study.

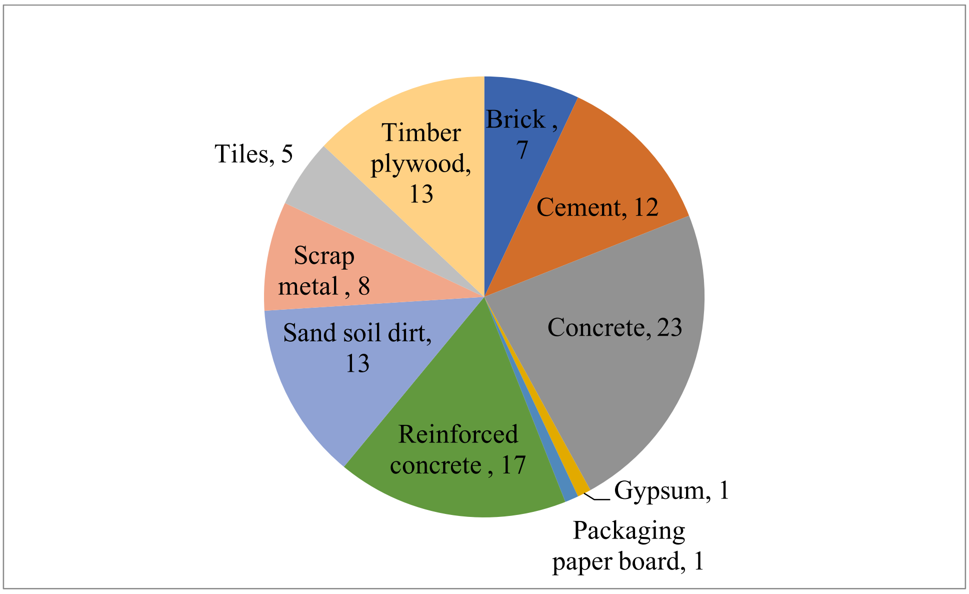

Figure 10: Conventional construction method waste composition (%)

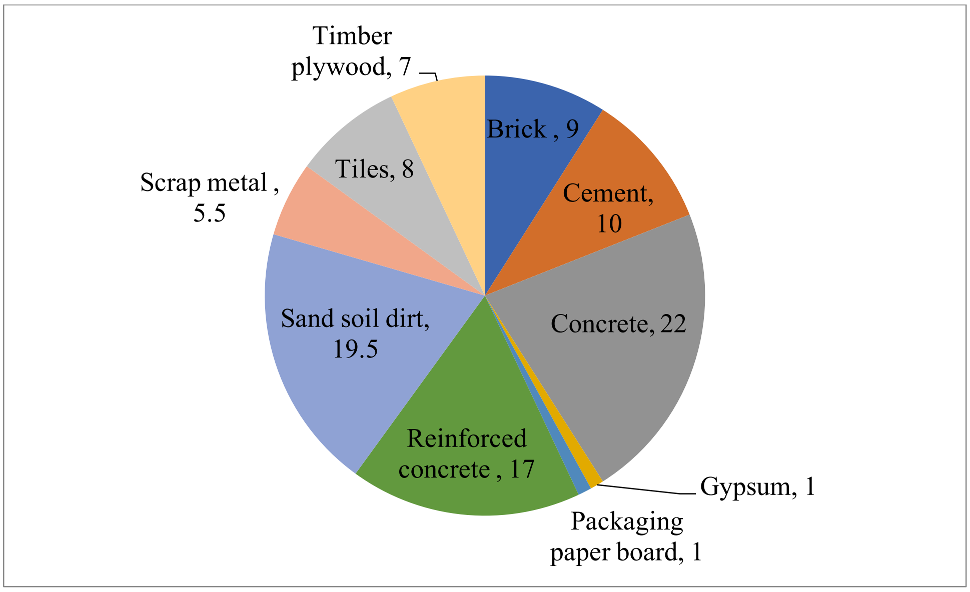

Figure 11: Mixed construction method waste composition (%)

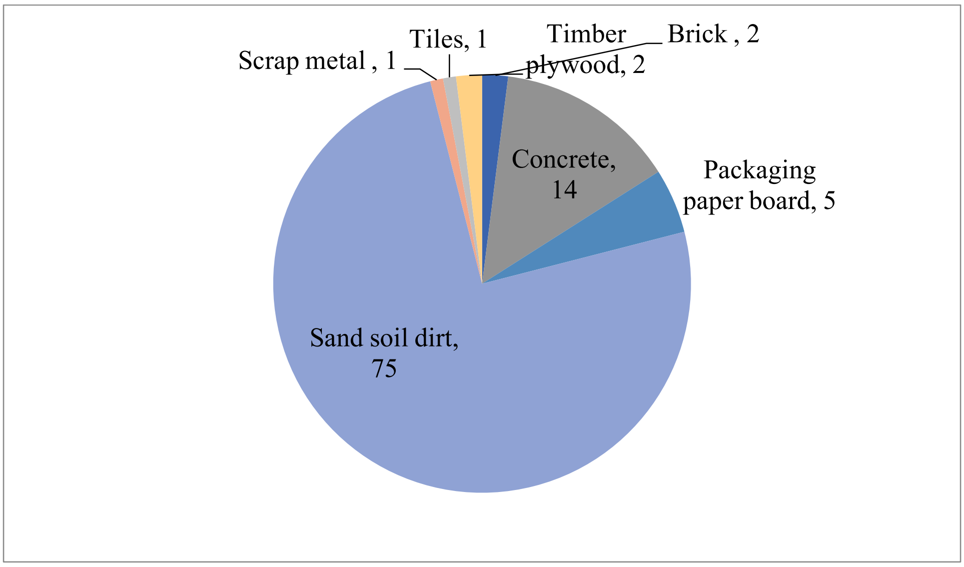

Figure 12: IBS construction method waste composition (%)

Waste composition (Table 12) multiplied with the waste generation in Table 9 to find the total waste generation based on construction method. Estimation results are illustrated in Figure 14, 15, and 16.

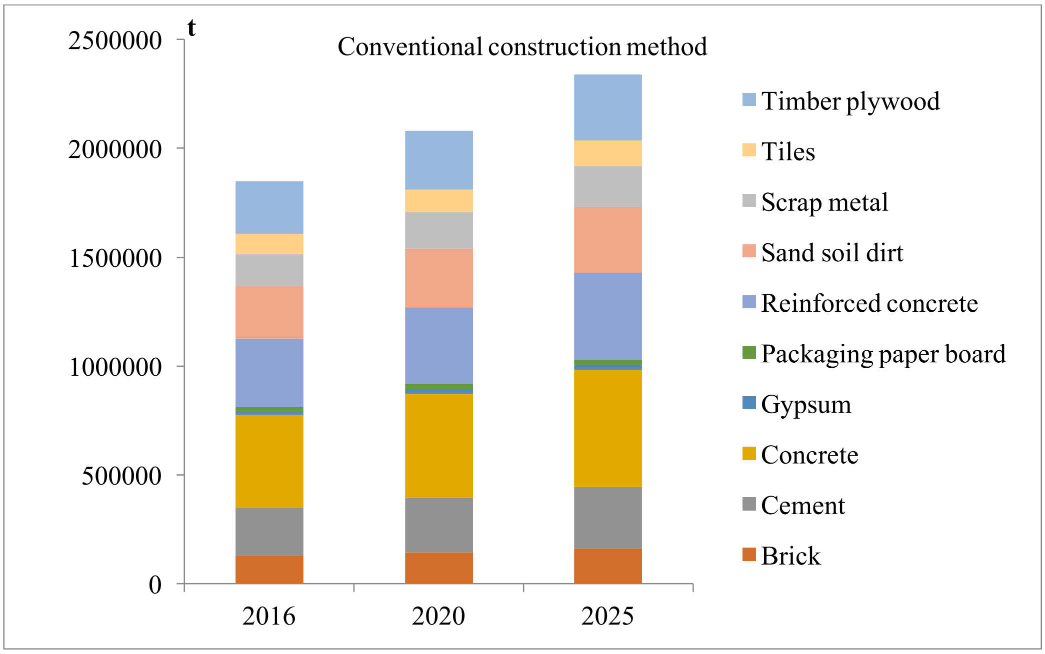

Figure 13: Conventional construction method - total waste generation by type

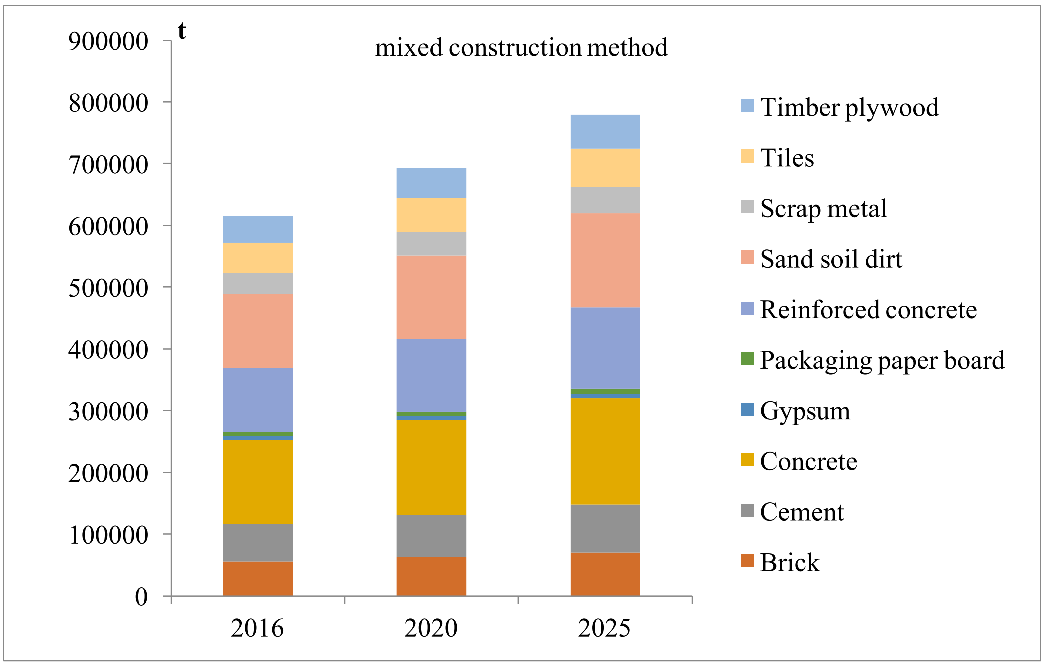

Figure 14: Mixed construction method - total waste generation by type

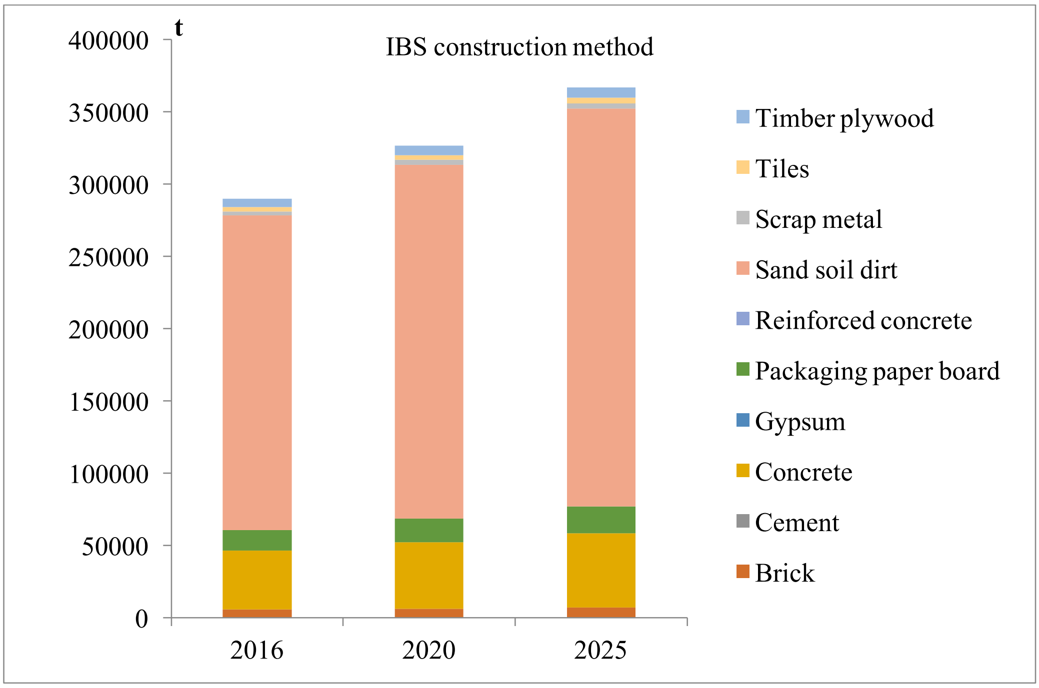

Figure 15: IBS construction method - total waste generation by type

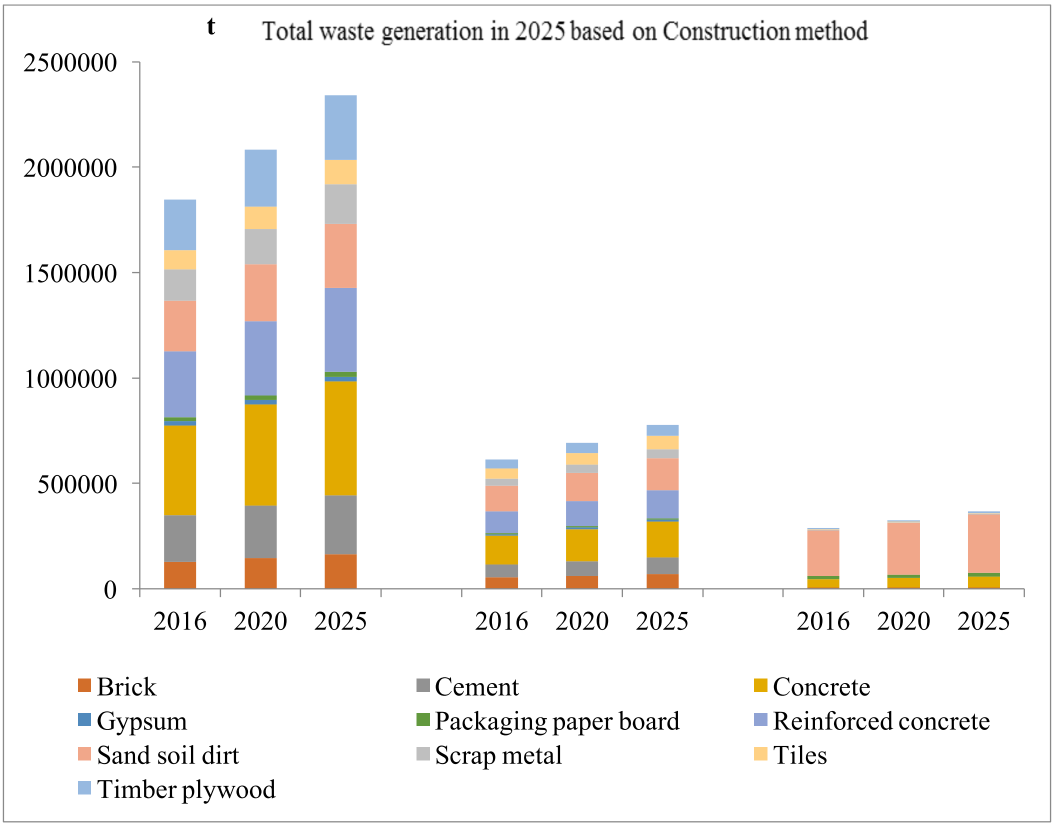

Figure 16: Total waste generation in 2016 -2025 based on conventional, mixed, and IBS construction method

4.8 Summary and Conclusion

Since the method used in this chapter makes use of readily available statistic data (total area built, construction cost, inflation rate, economy growth), the methodology used is well suited for periodic update when newer statistic data made available. According to Franklin Associates (1998b), waste assessment should change slowly over the time as the industry is known for it slow pace in adopting to changes. Composition of waste from building demolition should change even slower than waste from construction project.

There are a few crucial findings from this chapter that worth highlighting:

- An estimated of MYR 65.44 billion value worth of high rise residential construction work done by 2025.
- With the Malaysia's average inflation rate of 4 %, it is estimated that the cost of construction will increased to MYR 2,764 by 2025.
- Total area built by 2025 is extrapolated with a linear projection ($y = 3.2826x - 6581.8$, $R^2 = 0.8995$) at 23,680,297 m^2.
- With the WGR of 0.0988 t/ m^2 for conventional construction method, 0.0329 t/ m^2 for mixed construction method, and 0.0155 t/ m^2 for IBS project, the total waste generated in 2025, based on construction method are 2.34 million t, 0.78 million t, and 0.37 million t, respectively.
- C&DW composition based on different construction methods are recorded in table 20, 21, and 22.
- Economic growth extrapolation is usually subjected to many aspects. But in this study, linear projection is used due to the short term (9 years) study period.

The outcomes from this chapter are used in the next few chapters to estimate the future 2025 environmental impacts caused by C&DW.

References

Bina, J. U. (2017). Construction cost handbook Malaysia 2016 & 2017. from Malaysia: www.langdonseah.com (accessed Feb 12, 2017)

Department of Statistic, M. (2015). Quarterly construction statistics 2015 Quarter 1. Department of Statistics Malaysia Retrieved from https://newss.statistics.gov.my/newss-portalx/ep/epProductFreeDownloadSearch.seam (accessed December 20, 2015)

Department of Statistic, M. (2016). Economic cencus 2016 - Mining and quarrying. Department of Statistics Malaysia Retrieved from https://www.dosm.gov.my/v1/index.php?r=column/cthemeByCat&cat=97&bul_id=dVE3UXhFcVkzTFVPVXVWNkt6NDlpUT09&menu_id=TXdvYTlvQXVlTFhVOUJ6NVVESVBNUT09 (accessed July 20, 2017)

Lachimpadi, S. K., Pereira, J. J., Taha, M. R., & Mokhtar, M. (2012). Construction waste minimisation comparing conventional and precast construction (Mixed System and IBS) methods in high-rise buildings: A Malaysia case study. Resources, Conservation and Recycling, 68(0), 96-103.

5 Life cycle assessment of waste management

5.1 Life Cycle Assessment in Waste Management

Waste materials contribute to various environmental impacts throughout the different stages of life-time. Life cycle assessment is an assessment method used to accounts for the upstream and downstream benefits and trade-offs throughout the material's life-time. It is fundamentally aims to provide a structured and comprehensive approach in support for overall environmental impacts and to help to optimize the benefits.

Life cycle assessment (LCA) addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (ISO14044, 2006). In waste management, LCA is a useful tool used in conducting a systematic environmental impacts assessment focusing on evaluating the impacts or avoided impacts of different waste management scenarios. The LCA of waste management scenario, not covering the entire life cycle of the products which have become waste can differ from product LCA. LCA of waste management might play a smaller role comparing to the whole product LCA. However, due to the huge amount and bulky nature of C&D waste, some components of C&DW like plasterboard are hazardous once landfilled. It could break down and release hydrogen sulfide, a toxic gas in landfill.

Modelling waste disposal scenarios in life cycle assessment is an upside down version of the production model. Waste scenarios are the processes that refer to the material flows to end-of-life without observing the product characteristics. In waste scenarios, the information on waste material recycling processes are considered as subassemblies and the modelling of the subassemblies can be done through partial reuse or fully reuse operations.

In Bovea and Powell (2016) article, 71 (from 1999 – 2015) articles related to LCA in C&D waste management were reviewed. Analysis shows that 66.3 % of the total articles are conducted and published in European countries; like Spain, Italy, Portugal, and Sweden. 15 % of the articles are from USA, and 10 % of the articles are from Asia, which is dominated by China researchers. Bovea and Powell (2016) also highlighted that Asian countries have taken longer time to join in this research field. None of the 71 articles are from Malaysia though. In Laurent et al. (2014) article, 222 (from 1995 – 2002) articles published in 5 major waste management journals were reviewed. Two out of the 222 articles that were reviewed were conducted in Malaysia, focusing on LCA of municipal solid waste. Despite the increasing amount of C&D waste in Malaysia, none of the research identified by both of the authors studied LCA in C&D waste management. Laurent et al. (2014) however suggested that more research is needed to focus on C&D waste, which have been little assessed with LCA studies.

Both of the authors, Pasqualino, Ortiz, and Castells (2008) and Ortiz, Pasqualino, and Castells (2010) compared three scenarios in C&D waste management: landfilling, incineration, and incineration. Pasqualino et al. (2008) concluded that incineration is the best solution for hazardous waste, and recommended recycling for other inert materials for a construction in Barcelona, Spain. In (Ortiz et al., 2010) research, recycling is found to be the best option followed by incineration, and lastly, landfilling of C&D waste.

Balasbaneh and Marsono (2012) conducted a LCA in assessing 2 types of construction material alternatives in IBS frames (pre-cast concrete and prefabricated timber framing system). The study focused on the whole life cycle of IBS frames from extraction phase, use phase, maintenance phase, to end-of-life, waste treatment phase and concluded that prefabrication of timber framing system possessed less environmental impact compared to the latter. However, it is lack of transparency as the study boundary of both materials and the LCI studies are not well described in the article.

The main reason for this study to conduct LCA in C&DW in Malaysia is to access the unknown environmental impacts, GHG emissions in local waste management concept, and to access the potential recovery from recycling of C&DW in Malaysia. Study of LCA in C&DW management aims to provide basic knowledge on GHG emissions, impact assessment on human health, natural environment, and issues related to natural resource use.

The impact assessment from LCA is useful as a decision-making tool to improve the current C&DW management practice, and particularly important in the green economy transition (Ondova M., 2013). The life cycle assessment approach used in this study is defined in ISO 14040 and 14044 (ISO14040, 2006; ISO14044, 2006). There are four phases in LCA study:

- the goal and scope definition
- the life cycle inventory analysis (LCI)
- the life cycle impact assessment (LCIA), and
- the results interpretation

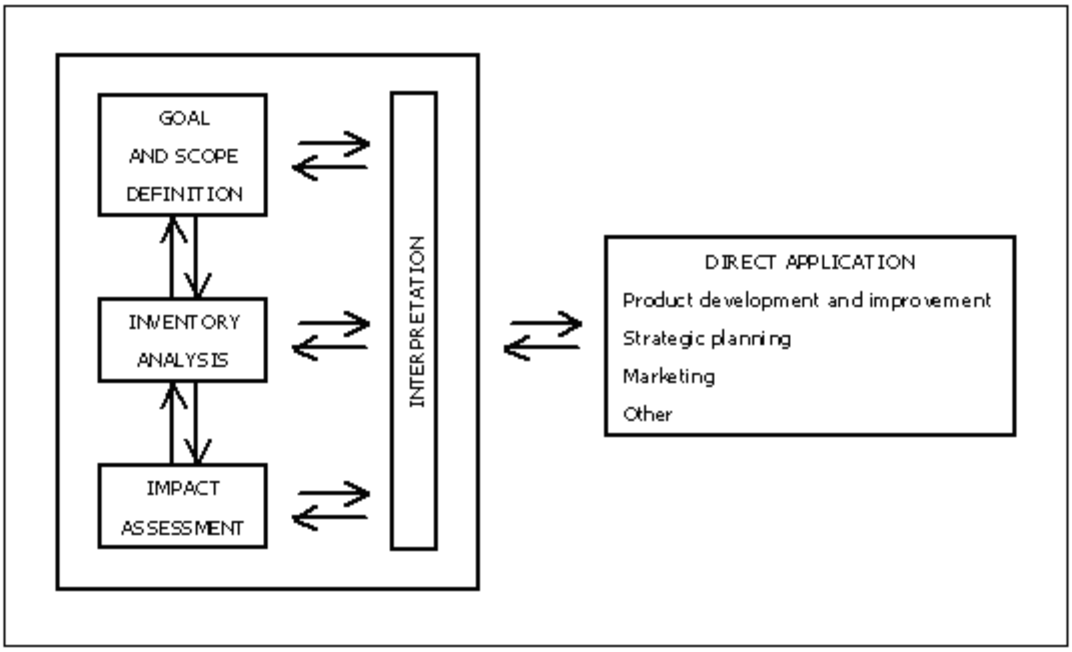

Figure 17: LCA Framework (ISO14040, 2006)

5.1.1 Goal and scope definition

The first part of an LCA study consists of defining the goal of the study and its scope. The goal of the study should include a statement of the reason for carrying out the study as well as the intended application of the results and the intended audience. In the scope of an LCA the following items shall be considered and described:

- The function of the product system.
- The functional unit.
- The system boundaries.
- Allocation procedures.
- Type of impact assessment methodology and interpretation to be performed.
- Data requirements.
- Assumptions and limitations.
- Data quality requirements.
- Type of critical review, if any.
- Type and format of the report required for the study.
- The scope should describe the depth of the study and show that the purpose can be fulfilled with the actual extent of the limitations.

5.1.2 Functional unit

The functional unit is a key element of LCA which has to be clearly defined. The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related. This enables comparison of two essential different systems. For example, the functional unit for a paint system may be defined as the unit surface protected for 10 years. A comparison of the environmental impact of two different paint systems with the same functional unit is therefore possible.

5.1.3 System boundaries

The system boundaries determine which unit processes to be included in the LCA study. Defining system boundaries is partly based on a subjective choice, made during the scope phase when the boundaries are initially set. The following boundaries can be considered:

Boundaries between the technological system and nature. A life cycle usually begins at the extraction point of raw materials and energy carriers from nature. Final stages normally include waste generation and/or heat production.

Geographical area. Geography plays a crucial role in most LCA studies, e.g. infrastructures, such as electricity production, waste management and transport systems, vary from one region to another. Moreover, ecosystems sensitivity to environmental impacts differs regionally too.

Time horizon. Boundaries must be set not only in space, but also in time. Basically LCAs are carried out to evaluate present impacts and predict future scenarios. Limitations to time boundaries are given by technologies involved, pollutants lifespan, etc.

Boundaries between the current life cycle and related life cycles of other technical systems. Most activities are interrelated, and therefore must be isolated from each other for further study. For example production of capital goods, economic feasibility of new and more environmentally friendly processes can be evaluated in comparison with currently used technology.

5.1.4 Life cycle inventory (LCI)

LCI comprises all stages dealing with data retrieval and management (see figure below). The data collection forms must be properly designed for optimal collection. Subsequently data are validated and related to the functional unit in order to allow the aggregation of results. A very sensitive step in this calculation process is the allocation of flows e.g. releases to air, water and land. Most of the existing technical systems yield more than one product. Therefore, materials and energy flows regarding the process as a whole, as well as environmental releases must often be allocated to the different products. This is recommended to be made according to a given procedure:

- Wherever possible, allocation should be avoided.

- Where allocation is not avoidable, inputs and outputs should be partitioned between its different functions or products in a way that reflects the underlying physical relationships between them.
- If the latter is not possible, allocation should be carried out based on other existing relationships (e.g. in proportion to the economic value of products).

The data collection is the most resource consuming part of the LCA. Reuse of data from other studies can simplify the work but this must be made with great care so that the data is representative. The quality aspect is therefore also crucial.

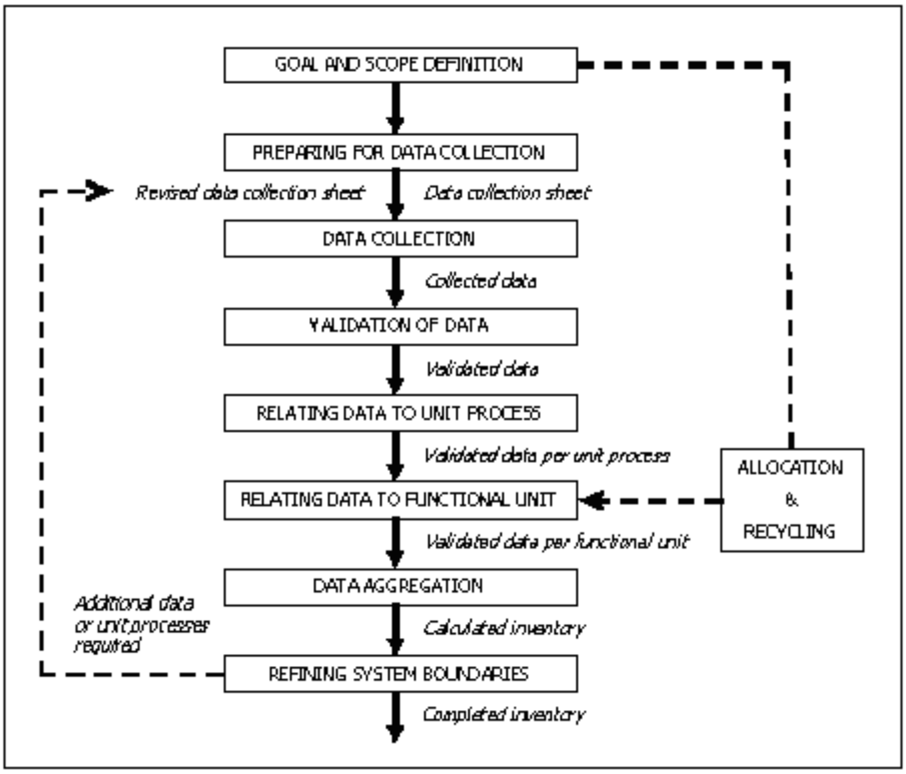

Figure 18: Development of LCI Framework (ISO14040, 2006; PRé, 2016)

5.1.5 Impact Assessment (LCIA)

LCIA aims to evaluate the significance of potential environmental impacts using the results coming out from the LCI phase. The ISO14040 suggests that this phase of an LCA is divided into the following steps:

Mandatory elements:

- Selection of impact categories, category indicators and characterization models.
- Classification, i.e. assignment of individual inventory parameters to impact categories, e.g. CO_2 is assigned to Global Warming. Common impact categories are Global Warming, Ozone Depletion, Photo oxidant formation, acidification, and eutrophication.
- Characterization, i.e. conversion of LCI results to common units within each impact category, so that results can be aggregated into category indicator results.

5.1.6 Interpretation

The aim of the interpretation phase is to reach conclusions and recommendations in accordance with the defined goal and scope of the study. Results from the LCI and LCIA are combined together and reported in order to give a complete and unbiased account of the study. The interpretation is to be made iteratively with the other phases.

The life cycle interpretation of an LCA or an LCI comprises three main elements:

- Identification of the significant issues based on the results of the LCI and LCIA phases of a LCA.
- Evaluation of results, which considers completeness, sensitivity and consistency checks.
- Conclusions and recommendations.

In ISO 14040 standard it is recommended that a critical review should be performed. In addition it is stated that a critical review must have been conducted in order to disclose the results in public.

5.1.7 The life Cycle Impact Assessment Method

Life cycle impact assessment (LCIA) stage is one of the stages defined in ISO 14040 (2006) to evaluate potential environmental impacts by using LCI inputs. LCIA involves aggregation of specific environmental impact categories into damage categories. Several LCIA methods have been developed, but in this study, the ReCiPe method is used to access the impact of the CDW waste management.

Life cycle impact assessment (LCIA) is an impact assessment of a series of life cycle inventories (LCI) in a LCA. It generally access three areas of protection: human health, natural environment, and issues related to natural resource use. LCIA aims at understanding and quantifying the magnitude and significance of the potential environmental impacts of a product or a service throughout its entire life cycle. Understanding these impacts is the first step in prevention, reduction and remediation actions. The impact assessment from LCA is useful as a decision-making tool to improve the current C&D waste management practice, and particularly important in the green economy transition (Ondova M., 2013).

5.1.8 ReCiPe method

The impact assessment method use in this study is ReCiPe method. References to the ReCiPe method is made based on PRé (2016) Simapro method manual. The method is the most recent and harmonized indicator approach available in life cycle impact assessment. The primary objective of the ReCiPe method is to transform the long list of life cycle inventory results, into a limited number of indicator scores. ReCiPe comprises two sets of impact categories with associated sets of characterization factors. At the midpoint level, 18 impact categories are addressed:

- Ozone depletion
- Human toxicity
- Ionizing radiation
- Photochemical oxidant formation

- Particulate matter formation
- Terrestrial acidification
- Climate change
- Terrestrial ecotoxicity
- Agricultural land occupation
- Urban land occupation
- Natural land transformation
- Marine ecotoxicity
- Marine eutrophication
- Fresh water eutrophication
- Fresh water ecotoxicity
- Fossil fuel depletion
- Minerals depletion
- Fresh water depletion

At the endpoint level, most of these midpoint impact categories are multiplied by damage factors and aggregated into three endpoint categories:

- Human health
- Ecosystems
- Resource surplus costs

5.1.9 Damage assessment

The endpoint characterization factors used in ReCiPe can be described as follows: Human Health, expressed as the number of year life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALYs), an index that is also used by the World Bank and WHO. The unit is years. Ecosystems, expressed as the loss of species over a certain area, during a certain time. The unit is years. Resources surplus costs, expressed as the surplus costs of future resource production over an infinitive timeframe (assuming constant annual production), considering a 3% discount rate. The unit is 2000US$ (Goedkoop, 2009).

The next chapter 6, 7, and 8 described the life cycle assessment studies based on different waste materials and system boundaries (Figure 19).

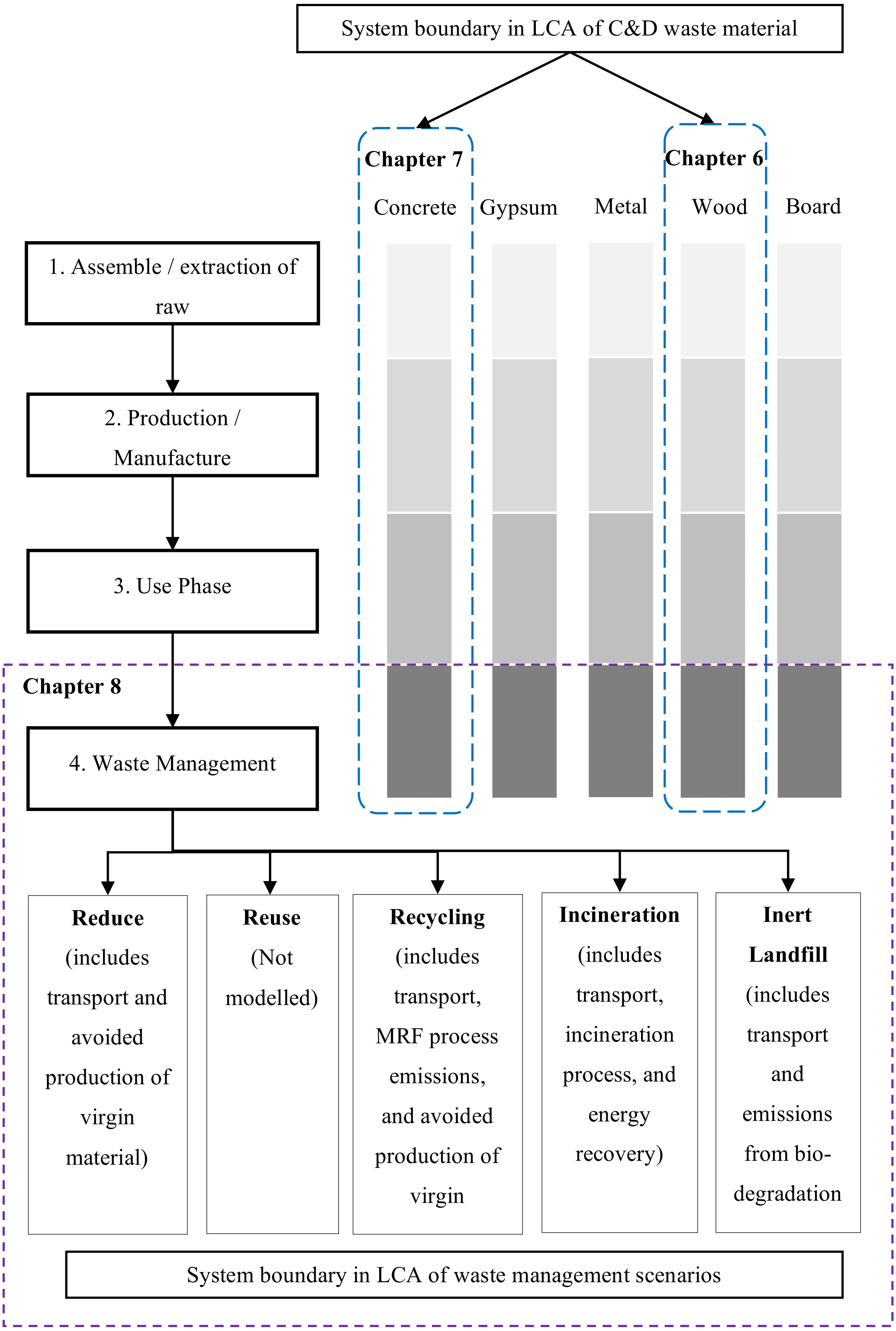

Figure 19: System boundaries for LCA in Chap 6,7, and 8.

References

Balasbaneh, A. T., & Marsono, A. K. B. (2012). Environmental Life-Cycle Assessment of a Single-Family House in Malaysia: Assessing Two Alternative IBS Frames. *International Journal of Emerging Technology and Advanced Engineering, 2*(11), 534 - 540.

Bovea, M. D., & Powell, J. C. (2016). Developments in life cycle assessment applied to evaluate the environmental performance of construction and demolition wastes. *Waste Management, 50*, 151-172. http://eplca.jrc.ec.europa.eu/uploads/waste-Guide-to-LCTLCA-for-C-D-waste-management-Final-ONLINE.pdf

Goedkoop, M. J. H., R.; Huijbregts, M.A.J.; De Schryver, A.M.; Struijs, J.; Van Zelm, R. (2009). ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level from Netherlands: http://www.lcia-recipe.net. (accessed Jan 19, 2017)

ISO14040. (2006). Environmental management — Life cycle assessment — Principles and framework.

ISO14044. (2006). Environmental management — Life cycle assessment — Requirements and guidelines.

Laurent, A., Bakas, I., Clavreul, J., et al. (2014). Review of LCA studies of solid waste management systems – Part I: Lessons learned and perspectives. *Waste Management, 34*(3), 573-588.

Ondova M., S. N. (2013). Environmental assessment of fly ash concrete. *Chemical Engineering Transactions, 35*, 841-846.

Ortiz, O., Pasqualino, J. C., & Castells, F. (2010). Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain. *Waste Management, 30*(4), 646-654.

Pasqualino, J. C., Ortiz, O. O., & Castells, F. (2008). Life cycle assessment as a tool for material selection and waste management within the building sector. *PLEA 2008 – 25th Conference on Passive and Low Energy Architecture*, Dublin.

6 LCA of Wood waste

6.1 Introduction

The objective of this study is to evaluate the potential environmental impacts associated with wood waste and to identify the best alternative in managing construction wood waste through life cycle assessment.

The outline of this study is presented in a few sections. Section 1 is the introduction, research purpose and objectives. Second section describes the research methodology, the scenarios development, assumptions, limitation, and life cycle inventory (LCI) data. Results analysis and discussion are presented in section 3. Lastly, the summary and conclusion are concluded in the last section of this study.

6.2 Goal definition, scope, and study boundary

A comprehensive life cycle assessment (LCA) framework for wood waste is proposed to assess the environmental impacts associated with different waste management strategy. This study will investigate the LCA in several different waste management strategy scenarios namely cradle to grave scenario where waste is sent to landfill without treatment and cradle to cradle scenarios that suggest recycling of wood waste to reduce the demand of virgin materials, and combustion of wood waste as an alternative to biofuel.

Figure 1 shows the life cycle stages of wood material and the system boundary of this study start at the point of extracting virgin wood from forest and end in end-of-life. Wood waste LCA is developed according to ISO 14040 and 14044. This research will focus on construction wood waste that is generated and discarded from construction project. Majority of the construction projects in Malaysia are constructed through traditional construction method where building components are being cast on-site, with timber and plywood. In traditional construction method, plywood is still widely uses in casting of slab, column, beam, and wall. Plywood uses in casting will eventually become waste regardless of the reusing cycle. Wood waste in this study is defined by the timber and plywood used as temporary formwork panel for casting the structural component of a building.

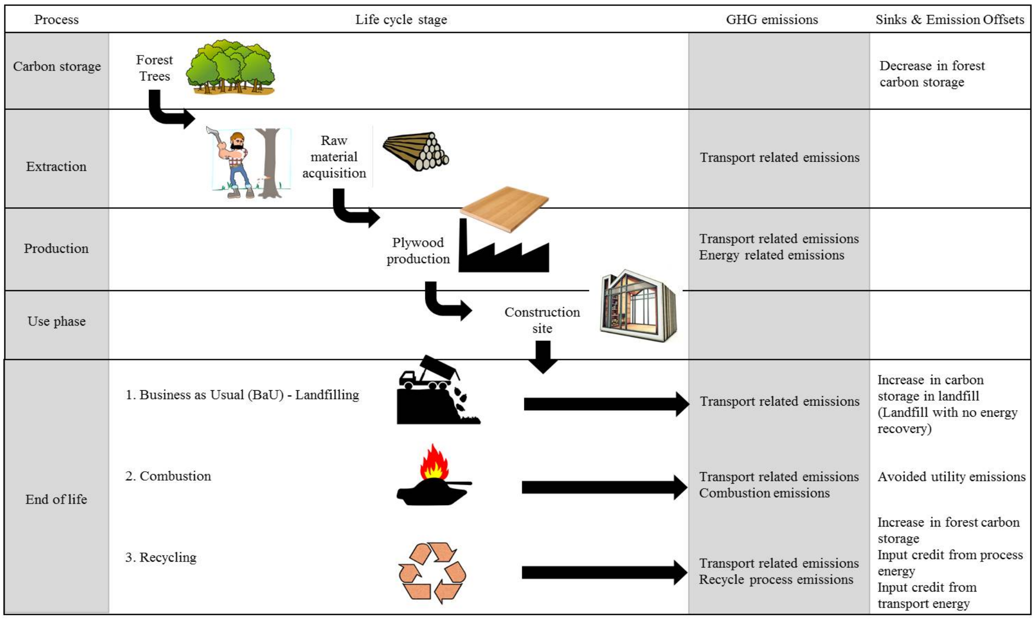

Figure 20: System boundary and life cycle of construction wood waste

6.3 Scenarios development

Scenario 1 – Business as Usual (Landfilling of wood waste)

S1 is the landfilling scenario. BaU is the current waste management strategy used in the industry, where all the wood waste produced from the construction site is dump to landfill without treatment. This study assumes that the landfill does not recover landfill gas (LFG). Organic matters especially wood do not decompose completely by anaerobic bacteria (Zeng, 2008) in landfill and most of the carbon is store in the landfill for many years. In landfilling, landfill of wood waste is considered as a carbon sinks and has a negative emission to the total GHG emissions. However, CH4 emissions generated from anaerobic digestion is considered in calculating the net carbon emission from landfilling.

The carbon emission for BaU scenario is calculated with:

Net carbon emission from landfilling = Forest carbon storage + Material emissions + production emissions + landfill carbon storage + GHG emissions from transportation

Scenario 2 – Incinerate wood waste with energy recovery

S2 is an alternative to BaU scenario where wood waste discarded from construction site is use in combustion as bioenergy material. In normal practice in Malaysia construction industry, if any of the wood waste is to send for combustion, it will usually have ended up as a burning material for residential heating purposes or informal business unit. In worst case scenario, developer or contractor will burn the wood waste illegally to save the handling fees and landfill cost. Open burning of wood waste creates many harmful carbon emissions to the atmosphere, nevertheless still serves as a biomass energy source. Therefore, the avoided utility emissions per waste combusted are considered in calculating the net emission from combustion. However, this study did not consider replanting of new trees (at source) to balance out with the number of wood waste burned.

The carbon emission for combustion scenario is calculated with:

Net carbon emission from combustion =Forest carbon storage + material emissions + production emissions + combustion emission + avoided utility emissions per waste combusted + emissions from transportation

Scenario 3 – Recycle of wood waste

Wood waste from construction is usually sorted out at site or at recycling facilities to determine the recyclability of the wood waste. In this study, it is assumed that 50% of the total wood waste is recyclable.

The carbon emission for recycling scenario is calculated with:

Net carbon emission from recycling = Forest carbon storage + material emissions + production emissions + recycle input credit process energy + recycle input credit transportation energy + forest carbon storage + emissions from transportation

6.4 Assumption and limitation

These assumptions and limitations were applied in this research:

- Resins that bind plywood together is not modelled in this study.
- Authors assume thirty percent (30%) of wood lost during the production stage through milling, shaping, and cutting processes.
- In landfilling and combustion, replanting of sources material (new tree) is not included in the study boundary. Therefore, CO2 emissions from combustion are calculated as part of the total emissions that are not recaptured back by replanting of new tree.
- In recycling, only 50% of total waste discarded is considered recyclable. Contaminated wood waste (e.g. nails, concrete, mortar, paint, dirt water, and etc) is considered non-recyclable.
- Landfill in this study is assumed to be a landfill without LFG recovery and the emissions are not considered as part of this study.

6.4.1 Functional unit

The functional unit of this study is the GHG emissions (kg CO_2 eq) per kg of wood waste discarded from construction site and the net GHG emissions of the three scenarios are calculated and compared in kg CO_2 eq / kg wood waste.

6.4.2 Life cycle inventories

This study analyzed the GHG sources and sinks from the upstream and downstream. Upstream and downstream emissions included the emissions derived from material emission, process emission, energy emission, transport emission, and resource depletion emissions. Emission factors in this study are adopted from United State Life Cycle Inventories (USLCI, 2013) and EPA waste reduction model (USEPA, 2016b) and the values extracted are adjusted according to the system boundary defined in this study (fig.1).

Forest carbon storage factor is -2.03 kg CO_2 eq, extracted from (USEPA, 2016b) material (meranti wood) emission factor is 0.69 kg CO_2 eq and production emission factor is 0.169 kg CO_2 eq.

GHG emissions associated with the transportation use in delivering wood from source to sink are identified from (USLCI, 2013) and Barge 1475 DWT is uses to transport raw material from source (forest) to production factory and the emission factor is 0.02 kg CO_2 eq /tkm. Truck and container (28 tons) is uses to transport the processed wood from production factory to construction site and the emission factor is 0.07 kg CO_2 eq /tkm. Single unit truck with diesel powered is uses as the main transportation to transport wood waste to end-of-life and the emission factor is 0.199 kg CO_2 eq /tkm (USLCI, 2013)

Landfill carbon storage that is without LFG recovery is identified as -1.04 kg CO_2 eq (USEPA, 2016b). The combustion emission factor is estimated from the total of CO_2 and N_2O emissions release from burning of wood waste and avoided utility GHG emission per kg of wood waste combusted. In combustion, carbon release from burning of wood waste is defined by the study boundary as non-biogenic (no regrowth of new tree at source to reabsorb the CO_2 produce in burning of wood waste). The CO2 (0.99 kg CO_2 eq) and N_2O (0.04 kg CO_2 eq) emissions is summed up to 1.14 kg CO_2 eq /kg (USEPA, 2016b). Avoided utility from combustion is -0.72 kg CO_2 eq /kg (USEPA, 2016b). Wood waste recycling emission factor is extracted from USEPA (2016) report with the net emission of -2.71 kg CO_2 eq.

6.4.3 Results and analysis

Results show that scenario 3 – recycling of wood waste emits the less GHG emissions at -2459.56 kg CO_2 eq /kg or wood waste recycled, followed by BaU - landfilling that emits -1901.39 kg CO_2 eq. Combustion emits the highest GHG emissions at -943.11 kg CO_2 eq. Compared to the landfilling and combustion of wood waste, recycling results in a larger increase in net carbon storage (an additional 558.16 kg CO_2 eq compared to landfill and an additional 1516.44 kg CO_2 eq compared to combustion).

In scenario 3, the emission from recycling wood waste is affected by the total amount of wood waste that is recyclable. In this study, it is assumed that only 50% of the total wood waste is recycled. Despite the emissions value in wood recycling is encouraging, the process is not without challenges. Often the contaminated wood waste that is not suitable for recycling will be discarded to either landfill or burn. If the process of removal of contaminants can be automated as well as more effective, it will help to improve the GHG emissions rate and also to reduce the number of wood waste sent to landfill.

6.5 Summary and conclusion of wood waste LCA

The main findings of this study can be summarized as follows: construction wood waste is better to be recycling than to be dump to landfill or for combustion. Transportation and distances between each point are the greatest influence of GHG emissions. Any savings in transport emission will reduce the total environment burden.

The emission factors used in this study are associated with data obtained from United States. With lack of directly applicable, published wood emissions data from Malaysia, the inventory provides a reliable, (if general, estimate) comparison in this study. Although the data does not reflect accurately to Malaysian wood waste industry, it is most usefully understood as an approximation in waste management decision making tool. To improve the accuracy of the results, authors suggest utilizing the waste inventory data from the same country, if available.

Table 13: Life cycle assessment for construction wood waste

LCA for wood waste											
			unit	Process step	Emission factor kgCO2eq	Result	Total (kgCO2eq) Landfilling	Combustion	Recycling	Source	Note
Forest carbon storage for 100% virgin outputs	1000		kg		-2.03	-2028	-2028.00	-2028.00	-2028.00	USEPA Warm Version 13 - Wood Product, pg.4	
Materials extraction											
Meranti FSC/PEFC	1000		kg	material	0.69	690	690	690	690	Idematapp2016 - Delft University of Technology	
Production											
Pressed raw plywood, from lay up, at plywood plant	700		kg	production	0.167	116.9	116.9	116.9	116.9	USLCI data	assume 30% of wood loss during production
Shaving of hardwood per kg dry mass	700		kg	processing	0.0026	1.82	1.82	1.82	1.82	USLCI data	
Transport	**km**	**t**									
Barge 1475 DWT	20	1	tkm	From raw material source to production factory	0.02	0.406	0.41	0.41	0.41	Idematapp2016	
Truck + container 28 tons net	50	0.7	tkm	Production factory to Construction Site	0.07	2.45	2.45	2.45	2.45	Idematapp2016	
Single unit truck, diesel powered / US	30	0.665	tkm	CS to landfill	0.199	3.970	3.970			USLCI data	
	30	0.3325	tkm	CS to landfill	0.199	1.985			1.99	USLCI data	
Single unit truck, diesel powered / US	5	0.665	tkm	CS to Combustion site	0.199	0.662		0.662		USLCI data	
Single unit truck, diesel powered / US	15	0.3325	tkm	CS to Recycling Facilities	0.199	0.993			0.993	USLCI data	
End of Life											
Landfilling											assume 5% waste loss at Construction site
Landfill carbon storage	665		kg		-1.04	-688.94	-688.94			USEPA Warm Version 13 - Wood Product	landfill without LFG recovery
Combustion	665		kg	CO2 and N2O emissions	1.13	751.45		751.45		Idematapp2016 - Delft University of Technology	
Combustion emissions	665		kg	avoided utility GHG per kg combusted	-0.72	-478.80		-478.80		USEPA Warm Version 13 - Wood Product, pg. 9	
Recycling											
Recycled input credit process energy	332.5		kg		0.077	25.66				USEPA Warm Version 13 - Wood Product	50% of total wood waste is recycled and 50% is dump to landfill
Forest Carbon Storage	332.5		kg		-2.79	-927.30				USEPA Warm Version 13 - Wood Product	
Landfill carbon storage	332.5		kg		-1.04	-344.47			-1246.11	USEPA Warm Version 13 - Wood Product	landfill without LFG recovery
							-1901.39	-943.11	-2459.56		

References

Lachimpadi, S. K., Pereira, J. J., Taha, M. R., & Mokhtar, M. (2012). Construction waste minimisation comparing conventional and precast construction (Mixed System and IBS) methods in high-rise buildings: A Malaysia case study. Resources, Conservation and Recycling, 68(0), 96-103. doi:http://dx.doi.org/10.1016/j.resconrec.2012.08.0 11

Mah, C. M., Fujiwara, T., & Ho, C. S. (2016). Construction and demolition waste generation rates for high-rise buildings in Malaysia. Waste Management & Research. doi:10.1177/0734242x16666944

USEPA. (2016). Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM). United States. Retrieved from https://www.epa.gov/sites/production/files/2016-03/documents/warm_v14_construction_demolition_materials.pdf

USLCI. (2013). The US life cycle inventory database version 2013 Retrieved from https://uslci.lcacommons.gov/uslci/search.from National Renewable Energy laboratory

Zeng, N. (2008). Carbon sequestration via wood burial. Carbon Balance and Management, 3, 1-1. doi:10.1186/1750-0680-3-1

7 Life Cycle Environmental and Economic Assessment of Concrete Waste

7.1 Introduction

Concrete is a bulky, voluminous, low-cost, and one of the essential material in modern structures. Concrete is produced by mixing portions of cement, water, sand, and aggregate. Annual global production of concrete is about 830 million tons. Twice as much as concrete is used in construction than other building materials such as wood, steel, or aluminum (Cement Association of Canada, 2016). In 2015, the cement production in Malaysia is at estimated at average 1.8 million tons (Department of Statistic, 2012-2015) and concrete waste (CW) accounted almost 60 % of total construction waste generated (Lachimpadi et al., 2012). The large amount of CW generated during the construction and demolition stages and the improper management of it often results in considerable environmental impacts.

Recycling and reusing of waste materials to produce new materials could eliminate the initial investment on primary production of natural materials and reduce environmental burdens. However, it is important to consider the burden of the recycling, reprocessing, as well as the quality of the recycled materials in the LCA (Rigamonti, Grosso, & Sunseri, 2009) to determine the CW recycling feasibility. Mercante, Bovea, Ibáñez-Forés, and Arena (2012) highlighted the importance of evaluating the environmental impact caused by different management strategies to assist in developing sustainable waste management. Bovea and Powell (2016) suggested that the comparison between natural raw material and recycled material environmental impact is vital, as the recycled material generates lower environmental impact than its equivalent primary material (Biswas, 2014). When CW is recycled and reused to produce RAC, S. Marinković, Radonjanin, Malešev, and Ignjatović (2010) concluded that the environmental impact of producing a RAC using the recycled concrete aggregate (RCA) is slightly lower than producing new concrete with NA. In Tošić, Marinković, Dašić, and Stanić (2015) study also suggested that 50 % substitution of NA with RCA resulted in lower environmental impact in the life cycle. RCA is also best to use as landfill daily cover material or road base material (Rosado, Vitale, Penteado, & Arena, 2017). The feasibility of both using NA and recycling RAC greatly depend on the travel distance between mining quarry to plant, and the type of transportation used to transport the NA too (S. B. Marinković, Ignjatović, & Radonjanin, 2013).

The persisting industry belief that recycling and reusing of CW materials is not a profitable economic decision discourages the exploration of recycling as an option (EU, 2011). The consideration of reduction in environmental impacts alone will not drive to the implementation of recycling, especially in the profit driven industry, where such is permitted to externalize pollution costs. Implementation of recycling practices will only arise where recycling shows direct economic benefit. Thus, it is important to consider economic indicator when evaluating the feasibility and to improve the eco-efficiency of waste recycling.

LCA is the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of the waste material throughout its life cycle (ISO14044, 2006). LCA typically excludes the evaluation of the economic aspects (ISO 14040) and economic impact analysis provides a good extension to the missing part of LCA. The economic analysis in LCA is known as life cycle costing (LCC). Another common economic method is the environmental life cycle cost (ELCC) which is the cost assessment that uses the identical system boundaries with LCA (Martinez-Sanchez, Kromann, & Astrup, 2015). The ELCC is a supplementary to LCA (Consonni, Giugliano, & Grosso, 2005) and it is used in this study to determine the economic indicator of waste management scenarios.

Both LCA and LCC are the tools to analyze both internal and external costs of a product or production within the same system boundary, on different model types with different units. The interpretation of the LCA and LCC results demonstrated in Carlsson Reich (2005) study, exploring the possibilities in linking economic data into waste management LCA study. There are three comman approaches in aligning the LCA and LCC results for interpretation: i) analyzing both as separate indicators, ii) analyzing it in environmental-cost ratio or cost-environmental ratio as eco-efficiency indicators, and iii) adding the both as common metric (Kloepffer, 2008). The both are added together with monetizing the environmental impact to allow the adding of LCA and LCC, for comparison and assessment using the same monetary unit (Carlsson Reich, 2005). In Ristimäki, Säynäjoki, Heinonen, and Junnila (2013) study, it assessed the combination results from LCA and LCC in term of viability through using the same method and presented the results in life cycle management perspective to support decision making in sustainable development.

There is no LCA and LCC study focus on CW management in Malaysia as highlighted by Bovea and Powell (2016) review. The main purpose of this study is to identify the most environmental cost efficiency waste management method for CW, by evaluating the environmental cost-effectiveness based on LCA and LCC studies. The study evaluates the potential environmental impact with LCA and economic impact with environmental LCC. Section 1 is the introduction, literature review, purpose, and objective. Section 2 describes the methodology, case study, and data collection, life cycle inventories, scenarios, and method to impact assessment. Results and discussion are presented in section 3 and section 4 discussed on the findings. The final section of the paper is the conclusion section.

A number of international researchers have devoted applicable research investigating the CW management and recycling rate (Lachimpadi et al., 2012). Bovea and Powell (2016) suggested that it is not only important to study the waste management in general, but the comparison between natural and recycled material is also important. S. Marinković et al. (2010); S. B. Marinković et al. (2013); Rosado et al. (2017); Tošić et al. (2015) investigated the environmental impact of natural aggregate (NA) and recycled aggregate concrete (RAC) through life cycle assessment (LCA) approach and the outcome reinforced the LCA method in decision making process especially in environmental impact assessment. In S. Marinković et al. (2010), Chowdhury et al. (2010), Simion, Fortuna, Bonoli, and Gavrilescu (2013), Knoeri, Sanyé-Mengual, and Althaus (2013), (Biswas, 2014) studies, they suggested that the recycled material generates lower environmental impact than its equivalent primary material. There are also studies that research the recycling of concrete waste to reproduces RAC as road base material (Rosado et al., 2017) so as to reduce the environmental burden of mining for NA material. Others who also studied on the environmental impact of CDW through life cycle assessment (LCA) (Bovea & Powell, 2016; Butera, Christensen, & Astrup, 2015; Ding, Xiao, & Tam, 2016; Mercante et al., 2012) highlighted the importance of evaluating the environmental impact caused by different C&D waste management strategies to assist in developing a sustainable waste management in the industry.

7.2 Methodology, case study and data collection

7.2.1 Case study and data collection

A total of seven (7) high-rise construction projects were selected as case study. The primary empirical data of CW generation rate were collected through periodic site observations conducted in the first half of 2015, including the sampling and measurement of waste containers to determine the amount of CW disposed out of site. The secondary data were also collected from interview on-site, reviewing of the monthly progress report, environmental management plan, sub-contractor claims and invoices, bill of quantities, and tender documents. The construction and demolition waste generation result is estimated with equation (1) that is published in Mah, Fujiwara, and Ho (2016).

$$WGR(concrete) = \frac{[total\ waste\ disposed\ (m^3)] \times [waste\ (concrete)\ composition\ (\%)] \times [waste\ (concrete)\ density\ (t\ m^{-3})]}{Floor\ area\ constructed\ or\ demolished\ (m^2)}$$

Table 14 shows the amount of CW generated from the 7 case studies from Iskandar Malaysia, Johor Malaysia. In Mah et al. (2016) paper, no recycling occured in the construction site (CS) and the waste generated were sent to landfill without treatment. The amount of waste material reused in the site is unknown and is excluded from the project total waste generation. The nearest MRF in Iskandar Malaysia City is selected to estimate the distances between each destination. Distances are recorded to reflect the actual travel distances rather than estimation (Table 14).

Table 14: Project details and travel distances

Project	Floor area (m^2)	Actual CW management cost (contract value) (MYR)	CW (t)	distances (km) d1 (CS-LF)	d2 (CS-MRF)	d3 (MRF-RCS)	d4 (MRF-CBP)	d5 (AMQ-RCS)	d6 (AMQ-CBP)
1	182,827	54,000	4,158	88	90	50	4	80	70
2	61,006	20,093	829	46	20	28	12	82	80
3	217,279	30,479	782	76	42	36	4	102	82
4	68,670	19,238	658	46	22	26	4	82	84
5	119,259	32,000	1,349	92	50	40	4	90	74
6	45,583	21,141	492	34	12	10	12	66	80
7*	128,985	78,014	27,288	44	17	22	12	64	80
	Average			60.9	36.1	30.3	7.4	80.9	78.6

*Note: * is a partial demolition and rehabilitation project of an abandoned commercial complex that produces a huge amount of waste as compared to the greenfield construction project 1-6.*

7.2.2 Life Cycle Assessment (LCA)

There are four phases in LCA study defined in ISO 14040 and 14044 (ISO14040, 2006; ISO14044, 2006). The LCA impact assessment (LCIA) is useful as a decision-making tool to improve the current CW management practice, and particularly important in the green economy transition (Ondova M., 2013).

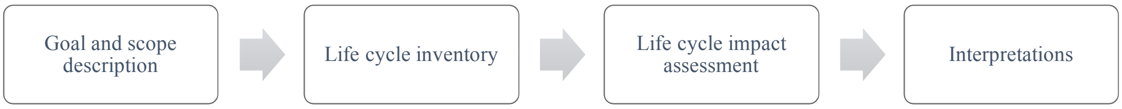

Figure 21: Life cycle assessment study approach

7.2.3 Goal and scope definition

The goal of this study is to estimate the GHG emissions of the CW management and to identify an effective management to reduce the impact. The LCA begins from the point of waste generation from construction site (CS) and included the impacts from production of new material when it is affected by the recycled waste material management decisions. The study considers recycling as an alternative to landfilling. Figure 22 shows the system boundary.

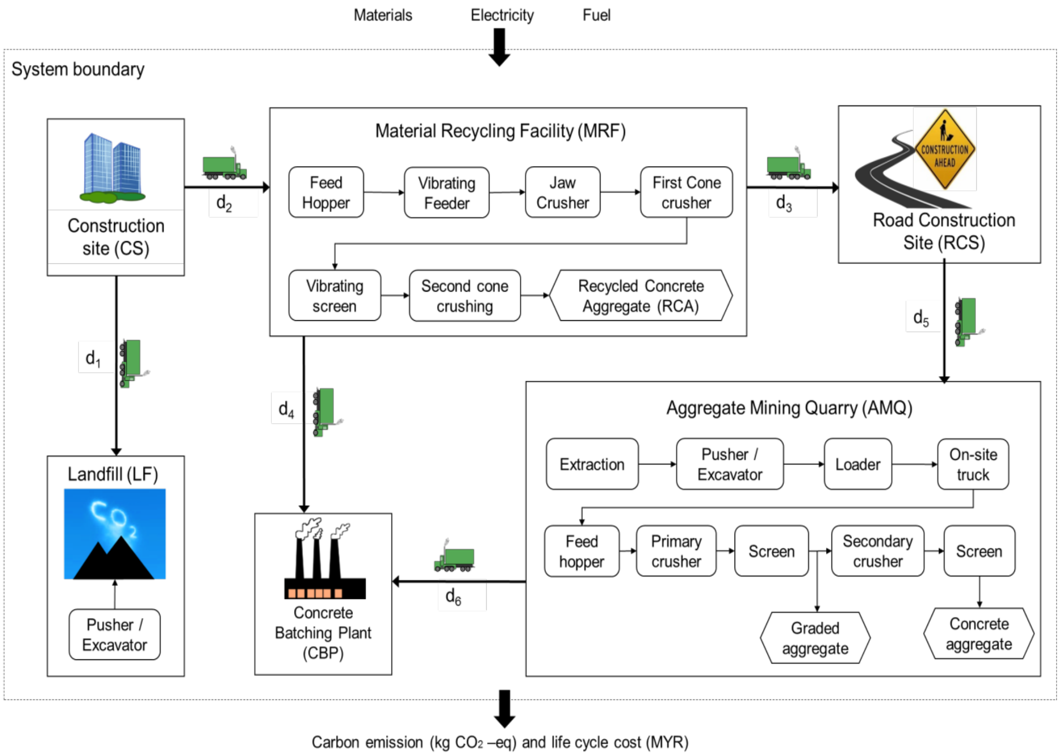

Figure 22: System boundary of CW life cycle assessment

These assumptions and limitation were applied in this study:

- CW material is an inert waste which is neither chemically or biologically reactive and will not decompose in landfill.
- Carbon emissions emitted by calcination process in cement production is the major contributor in concrete production and this emissions is unavoidable. The CO_2 emission from cement material is accounting for almost 92.7% of the total GHG, concrete manufacture phase accounted only 7.2% of the total GHG emissions (Ma, Sha, Yang, & Huang, 2016). Cement material emissions from calcination process in production stage is allocated to the primary user of the material. It is not excluded from this study.
- In RAC production, there are limit to the percentage of replacement of NA by RCA. In Hong Kong and New Zealand, up to 100 % of RCA replacement is allowed and the RAC produces is acceptable for all non-structural applications

(Zealand, 2011). Meanwhile, in countries like UK, Australia, Korea, Germany, Portugal and Hong Kong, the allowable RCA substitution for structural concrete range from 20 % to 35 %, depending on the required RAC strength (Zealand, 2011). However, the usage of RCA in RAC is likely to influence most of the concrete properties such as compressive strength, modulus of elasticity, shrinkage, and creep. The relative density of RCA is about 5 % - 10 % lower than the NA because of the cement mortar that remains adhered to the aggregate. Nevertheless, RAC can be manufactured using 100 % RCA replacement where the processing of the RCA and the manufacture of the RAC are all closely controlled (Zealand, 2011). The natural carbonation process occurs in building concrete and the uptake of CO_2 in re-carbonation of RCA are both not considered in this study.

- The concrete mixture ratio 1 part of cement, 3 parts of sand, and 3 parts of gravel / aggregate will produce a concrete mix of approximately 3000 psi. In this study (Scenario 2, 3, and 4), 1 t of RCA is assumed to have replaced the gravel / aggregate portion in the concrete mix.
- The carbon footprint of the construction of MRF, concrete batching plant (CBP), and construction of machineries are excluded in this study.

7.2.4 Scenario model calculations development

The assessment focused on the recycling and landfilling of CW. CW originates from CS and flow to either landfill or recycling path. To compare the sustainability of the waste management approaches, one cradle-to-grave and three cradle-to-cradle scenarios are developed (Figure 23).

Scenario 1 (S1) is the business as usual scenario (BaU) where the CW generated from CS is sent to landfill without treatment. This scenario is also known as cradle to grave where the environmental impacts are assessed from material extraction through material end-of-life. This total landfilling scenario reflects the current CW management practices in Malaysia and is set to be the baseline for scenarios comparison with S2, S3, and S4. The amount of CW produce from the CS is assumed to be at *w* amount. Within the system boundary, road construction site (RCS) requires *x* amount of NA and CBP requires *y* amount of NA. Neither the RCS nor the CBP are benefited from the CW. Thus, the demands from RCS and CBP are both fulfilled by aggregates mining quarry (AMQ) supplying *(x+y)* amount of NA. Figure 3 shows the materials flow and table 1 depicted the emissions calculation model of S1 to S4 (detail calculation at Appendix 1).

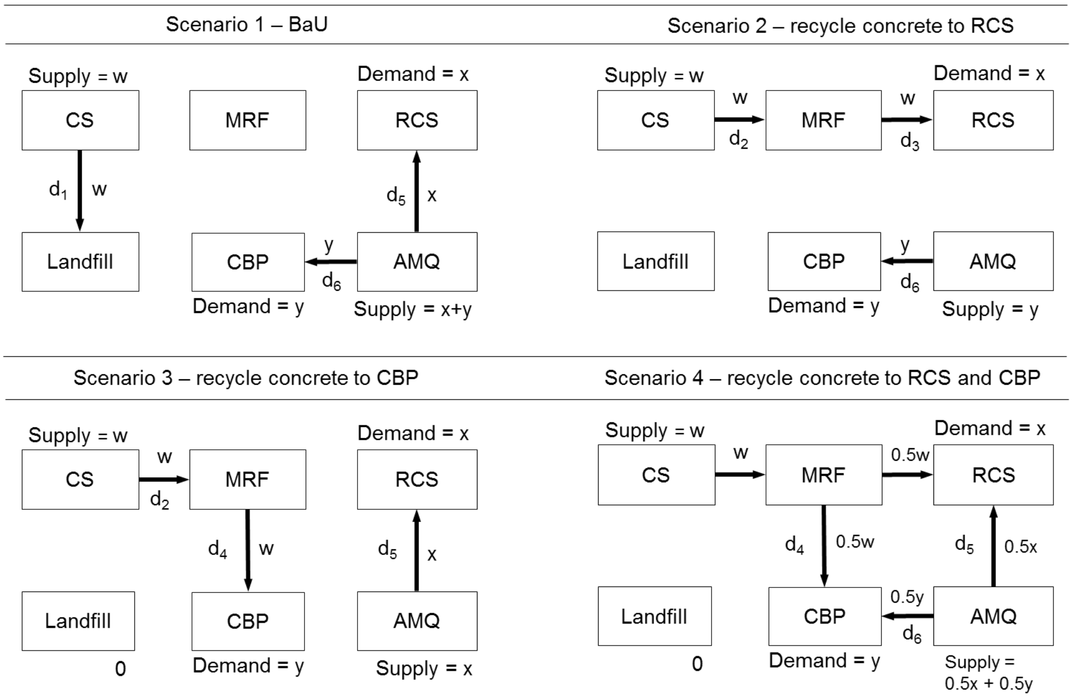

Figure 23: System boundary for scenario 1-4.

Scenario 2, 3, and 4 describe the cradle-to-cradle concept, where the CW end-of-life is a cyclical reuse and recycling process. Instead of dumping CW to landfill, CW is recycled into RCA for secondary material reproduction application. Recycling of concrete will lead to reduction of GHG emissions as it reduces the burden in mining activity. It is a concept used to minimize the environmental impacts in supporting sustainable waste management.

Scenario 2 (S2) is where the CW is crushed to sizes to produce RCA and reused as road base material in RCS. CW generated from CS is diverted from landfill to MRF for recycling. RCA is reused to reduce the demand of NA. The w amount CW is sent to the MRF, crushed to reproduce RCA and later w is sent to RCS. The w is assumed to have fulfilled the x amount of RCS demand on NA (w=x). AMQ supply only y amount to the CBP.

Scenario 3 (S3) is where the entire CW is crushed to produce RCA and reused in CBP to produce RAC. The w amount of CW is sent to the MRF, crushed to reproduces RCA and later w is sent to CBP. In CBP, RAC is produced using RCA. The w is assumed to have fulfilled the y needed in CBP (w=y). The AMQ supply only x amount to the RCS.

Scenario 4 (S4) is where the entire CW is crushed to produce RCA. It is assumed that 50 % of it is used in RCS and another 50 % is used in CBP to produce recycled aggregate concrete (RAC). S4 is also the intermediate scenario between S2 and S3. It is assumed that the allowable substitution of RCA is 50 % (NA : RCA = 1:1) to produce a unit of RAC. The CBP demand on aggregate to produce a unit of RAC is y = 2w. The entire CW is crushed to produce RCA and reused in both RCS and CBP with a split of 50 % each. Supply from AMQ to the CBP is defined as (y - 0.5w) and the supply to RCS is defined as (x - 0.5w).

Table 15: Scenario model calculation for S1-S4

	Emission factor			Cost factor		
S1: Business as Usual	Transportation ($kg\ CO_2\ eq\ /t$)	LF machinery ($kg\ CO_2\ eq\ /t$)	Mining ($kg\ CO_2\ eq\ /t$)	Transportation (MYR /t)	Landfill (MYR /t)	Mining (MYR /t)
CW sent to landfill	$E_t \times w \times d_1$	$E_{LM} \times w$		$C_t \times w \times d_1$	$(C_{LF} + C_{LM}) \times w$	
Mining of NA for RCS	$E_t \times x \times d_5$		$E_m \times x$	$C_t \times x \times d5$		$C_m \times x$
Mining of NA for CBP	$E_t \times y \times d_6$		$E_m \times y$	$C_t \times y \times d6$		$C_m \times y$
Total S1	$\boldsymbol{E_t (w \times d_1 + x \times d_5 + y \times d_6) + E_m (x + y)}$			$\boldsymbol{C_t (w \times d_1 + x \times d_5 + y \times d_6) + C_m (x + y) + C_{LF} + C_{LM}}$		
S2: Recycle CW for RCS	Transportation ($kg\ CO_2\ eq\ /t$)	Mining ($kg\ CO_2\ eq\ /t$)	Recycling ($kg\ CO_2\ eq\ /t$)	Transportation (MYR /t)	Mining (MYR /t)	Recycling (kg CO2-e /t)
Recycling CW in MRF	Et × w × d2		Er × w	Ct × w × d2		Cr × w
Supply of RCA from MRF to RCS	Et × w × d3			Ct × w × d3		
Mining of NA for CBP	Et × y × d6	Em × y		Ct × y × d6	Cm × y	
Total S2	**[Et × (d2 + d3) + Er] × w + [Et × d6 + Em] × y**			**[Ct × (d2 + d3) + Cr] × w + [Ct × d6 + Cm] × y**		

S3: Recycle CW for RCS and CBP	Transportation (kg CO_2 eq /t)	Mining (kg CO_2 eq /t)	Recycling (kg CO_2 eq /t)	Transportation (MYR /t)	Mining (MYR /t)	Recycling (kg CO2-e /t)
Recycling CW in MRF	$E_t \times w \times d_2$		$E_r \times w$	$C_t \times w \times d_2$		$C_r \times w$
Supply of RCA from MRF to RCS	$E_t \times 0.5w \times d_3$			$C_t \times 0.5w \times d_3$		
Supply of RCA from MRF to CBP	$E_t \times 0.5w \times d_4$			$C_t \times 0.5w \times d_4$		
Mining of NA for RCS	$E_t \times (x - 0.5w) \times d_5$	$E_m \times (x - 0.5w)$		$C_t \times (x - 0.5w) \times d_5$	$C_m \times (x - 0.5w)$	
Mining of NA for CBP	$E_t \times (y - 0.5w) \times d_6$	$E_m \times (y - 0.5w)$		$C_t \times (y - 0.5w) \times d_6$	$C_m \times (y - 0.5w)$	
Total S3	$\boldsymbol{[E_t \times d_2 + E_r] \times w + (E_t \times 0.5w) \times (d_3 + d_4) + [Et \times d5 + Em] \times (x - 0.5w) + [Et \times d6 + Em] \times (y - 0.5w)}$			$\boldsymbol{[C_t \times d_2 + C_r] \times w + (C_t \times 0.5w) \times (d_3 + d_4) + [Ct \times d5 + Cm] \times (x - 0.5w) + [Ct \times d6 + Cm] \times (y - 0.5w)}$		

S4: Recycle CW for CBP	Transportation (kg CO_2 eq /t)	Mining (kg CO_2 eq /t)	Recycling (kg CO_2 eq /t)	Transportation (MYR /t)	Mining (MYR /t)	Recycling (kg CO2-e /t)
Recycling CW in MRF	$E_t \times w \times d_2$		$E_r \times w$	$C_t \times w \times d_2$		$C_r \times w$
Supply of RCA from MRF to CBP	$E_t \times w \times d_4$			$C_t \times w \times d_4$		
Mining of NA for CBP	$E_t \times x \times d_5$	$E_m \times x$		$C_t \times x \times d_5$	$C_m \times x$	
Total S4	$\boldsymbol{[E_t \times (d_2 + d_4) + E_r] \times w + [E_t \times d_5 + E_m] \times x}$			$\boldsymbol{[C_t \times (d_2 + d_4) + C_r] \times w + [C_t \times d_5 + C_m] \times x}$		

E_{LM} = emission from landfill machineries E_r= emission from MRF, E_t = emission from transportation, E_m = emission from mining, , C_t = transportation cost, C_m = cost of mining, C_{LF} = landfill tipping fee, C_{LM} = landfill machinery emission, C_r = cost of recycling in MRF

7.3 Life cycle inventories

The life cycle inventories (LCI) analysis of this study involves the assessment and the compilation of inputs and outputs of CW management throughout its life cycle. Data collection was conducted through site surveys and interviews from 2015 to end of 2016. Site interviews were conducted with industry professionals. Input data of machineries, truck, energy, fuel consumption, and waste input were obtained from site. The details of machineries and trucks used were collected from catalogues and literature reviews from published documents. The impact assessment and output are calculated utilizing Simapro 8.4.0.0 PhD version software, a program regularly utilized in academic research. LCA study in Malaysia is rather new and the LCI databases in CW in Malaysia is either not available or of poor data quality. There are limitations in collecting or accessing the primary data (such as Natural aggregate material emission, details of mining industry which involves commercial confidentiality). This study is obliged to utilize the proxy data (industry average) obtained from ecoinvent 3.3 (2016) database to complement with the primary data. Technological similarities between processeses are considered as the selection criteria. Impact assessment covered three main GHG (CO_2, CH_4, and N_2O) emissions are recorded in CO_2 equivalents for comparison. The environmental impact category focused on the 100-year global warming potential (GWP 100a) and the assessment method was according to IPCC GWP 2013 100a. Recycled concrete used as road base material or building material is rarely demolished or dismantled even after the end-of-life (Butera et al., 2015). GWP 100-year is sufficiently represents the foreseeable environmental impact in this study.

7.3.1 Landfilling of concrete waste

Landfilling of CW requires transportation to transport the CW from CS to LF. The input to landfilling derived from landfill compactor machinery, waste truck used in transporting waste, and the output is 0.411 kg CO_2 eq per ton of concrete waste landfilled (Table 17). No direct emissions from inert material landfill (leachate) are inventoried as deemed negligible.

7.3.2 Recycling of concrete waste in material recycling facilities (MRF)

Material recycling process flow was constructed following a site visit to one of the MRF in November 2016. CW is usually transported in a fully loaded; diesel powered 20 t waste trucks to the MRF. From the site visit, the machineries used in the MRF are sketched in Figure 4. The machineries specification is extracted from the manufacturer. The initial sorting stage is manual material triage of the material to determine the recyclability for the maximal value creation. Manual material triage process is excluded in LCA as it does have direct GHG emissions, but the labor cost (2 people) was considered in LCC. The process begins with incoming clean CW and reinforced concrete is loaded on the feed hopper. Non-acceptable materials are hand sorted and also screened off before sending it into jaw crusher. After the primary crusher, the material passes under a magnetic belt where scrap metal is screened off before being transfer to the first cone crusher that further crush the CW into smaller sizes. The material will then be screened through vibrating screen and the oversized material will be recirculated back into the second cone crusher (Figure 24). Recycling machineries require 3.11 kWh /t to process 1 ton of concrete waste and is powered by electricity supply from the grid. The output is 2.52 kg CO_2 eq /t (Table 17).

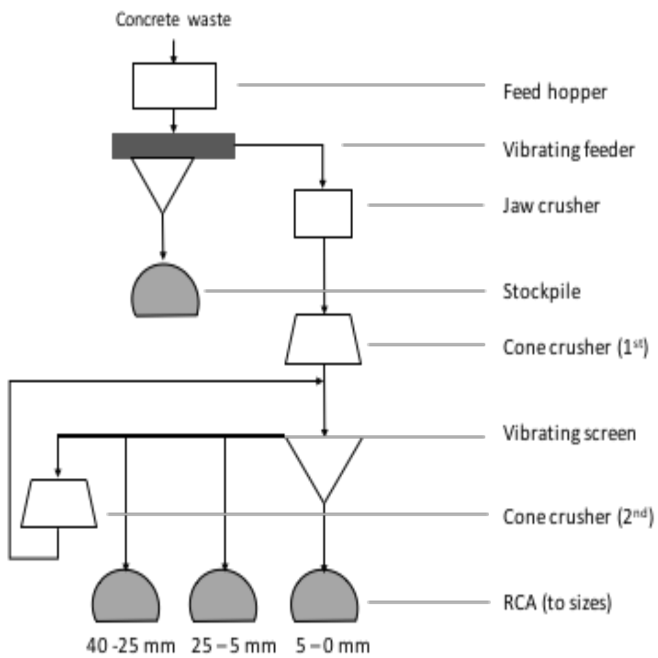

Figure 24: System model of recycling machineries in MRF

7.3.3 Mining of natural aggregate in quarry

The process flow of mining of NA is depicted in Figure 25. Drilling and blasting processes are excluded from the system boundary as there is no adequate and reliable data on it. The system flow starts at extraction phase where an extractor and a pusher were employed to extract and push the NA rocks to the hauling area. After the extraction, loaders were used to load the rock into a payload capacity haul truck. Extractor, pusher and loaders are powered by diesel power. The distance between the mining pits to the processing center is assumed at 1km (return trip) within the quarry. At the processing center, the material is loads into the feed hopper and crushed. Then the material enters onto the conveyor of the vibrating screen and then to the scalping screen. Scalping screen is uses to shake and separate the oversize material to pass over to stock pile and the others fall into the jaw crusher. Then the material goes through two vibrating feeder and into a cone crusher where the material is crushed into smaller size. NA of different sizes pass through the last vibrating screen and the oversize is recirculated back to the final crusher. The mining machineries require electricity powered by at-grid of 14.06 kWh /t to mine and process 1 t of NA (Table 17). The GHG emissions is 8.1 kg CO_2 eq /t of NA produced.

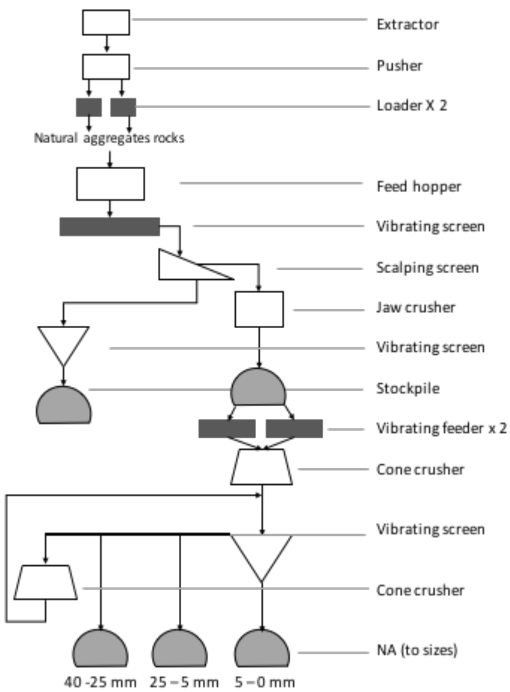

Figure 25: System boundary of mining of NA

7.3.4 Assemble of concrete with natural concrete and recycled aggregate concrete

The environmental impacts differences between assembling new concrete with 1 t of NA and assembling RAC with 0.5 t of RCA are recorded in table 4. The differences between replacing 100 % of NA and RCA is 17.86 kg CO_2 eq /t of RAC produced. The material emissions ofRCA is considered in the earlier production life cycle and is beyond the study boundary. The emission from RCA material is assumed to be zero.

7.3.5 The transportation

The transportation used in this study is the 16-32 t lorry truck and off-road CAT 785D mining truck. The impact category is recorded in Table 3 and 4.

Table 16: LCI calculation for off-road mining truck

CAT 785D mining truck	Liters of fuel used	Power	Dump load	Fuel consumption	Emission	Total emission
	(L /h)	kW	t	(L /th)	kg CO^2 eq /L	kg CO^2 eq /th
	118.25	1082	136.1	0.87	2.66	2.31

Table 17: Summary of LCI data

		Input	Unit	Output kg CO_2 eq	Note
Transportation, freight, lorry 16-32 ton		1	tkm	0.164	
Landfilling 1 ton of concrete wste					
Landfill machinery - compactor		0.794	m3	0.411	
Mining 1 ton of natural aggregate				8.10	
Mining operation (diesel powered)		10.75	kWh /t	3.12	
Extraction (CAT D9R dozzer)	4.69				
Pusher / Excavator (CAT 330C excavator)	2.47				
Loader (Volvo L180F 265kW)	3.59				
Process 1 t of NA		3.31	kWh /t	2.67	
Feed hopper					
Vibrating feeder	0.13				
Scalping screen	0.09				
Jaw crusher	0.67				
Vibrating screen	0.13				*
Stock pile					
Vibrating feeder	0.09				
Cone crusher	0.92				
Vibrating screen	0.38				
Cone crusher	0.92				
Transportation, off-road mining truck CAT785D		0.87	L /th	2.31	**
Recycling 1 ton of Concrete waste in MRF		3.11	kWh /t	2.52	
Feed hopper	0.00				
Vibrating feeder (QH-1042)	0.14				
Jaw crusher (FSK-4430)	0.69				
First cone crushing (MC-200(A))	1.00				
Vibrating screen (OP3-2160)	0.28				
Second cone crushing (MC-200(B))	1.00				
Material emission					
Natural aggregate		1	t	17.86	***
Recycled concrete aggregate		1	t	0	****

** Machineries details are obtain from Samyoung Plant Co. (2016).*

*** The distance between quarry to processing unit within the quarry vicinity is assumed to be 1 km (return trip).*

**** natural aggregate material emission data is adopted from ecoinvent 3.0 database, crushed gravel, global average, and system allocation dataset.*

***** Recycled material is free of burden from upstream processes. RCA is considered as burden-free and bear only the impacts of recycling processes.*

******Refer Appendix B for detail estimation and calculation of each LCI processes.*

7.4 Life Cycle Cost (LCC) Inventory

Life cycle cost inventory were conducted according to the LCA study boundary. In combination with a LCA, LCC address the economic dimension of sustainability of the selected waste management approach. The development of this study LCC is based on figure 28.

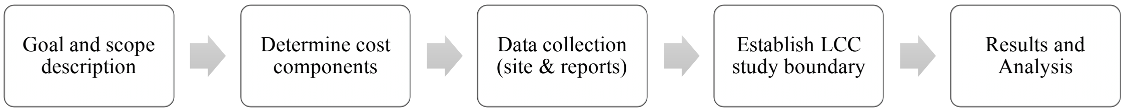

Figure 26: Life Cycle Cost analysis

However, there are exclusion in the LCC study due to data availability and data consistency:

- Capital cost of building a MRF, CBP, truck, machineries are all excluded just as like in LCA study to exclude carbon footprint of the construction and building.
- Environmental pollutant substances costs are excluded due to data availability and consistency.

7.4.1 Landfilling of concrete waste

Landfill tipping fee differs according to location and technology employed in the landfill. The fee ranges from MYR 10 to MYR 40 /t. This study used an average landfill tipping fee of MYR 25/t. Machinery used in inert landfill is a compactor. Dumping truck usually drives up onto the compacted landfill to make the dumping, excavator is not employ due to cost saving. The cost factor for landfill machinery is estimated at MYR 1.05 /t (Detail at appendix B).

7.4.2 Recycling of concrete waste in material recycling facilities (MRF)

The cost of recycling are calculated based on energy consumption of 3.11 kWh to recycle 1 t of CW. With the unit rate of MYR 0.38 /kWh, cost of recycling is calculated at MYR 1.18 /t of CW recycled.

7.4.3 Mining of natural aggregate in quarry

Quarry mining cost data obtained from Department of Statistic Malaysia, Concensus data of quarry activity in Malaysia (Department of Statistic, 2016).

Table 18: Statistics of quarrying sector in 2015

	Total	unit cost
Gross output (RM)	7,120,000,000	16.50
Gross production (t)		431,515,152
Employees (person)	28,168	
Salary paid (MYR)	816,000,000	
Labor cost (MYR/hr)		11.61
Raw material costs (MYR)	2,275,392,000	5.27
*Operation costs (MYR)	2,078,957,000	4.82
Total cost (MYR)	4,354,349,000	
Cost of production (MYR /t)		10.09

**Operation costs included electricity, water, fuels, lubricants, gas, repairs and maintenance of assets, earth removal, and internal transport in quarries.*

Surveys with 2 landfills in Malaysia revealed that RCA materials were recycled and reused as daily cover material in the landfill. Due to the inert characteristic landfill, daily cover material is not important and does not necessarily trigger a cost saving. In LCC, cost saving from reusing RCA as landfill cover is considered as zero. RCA material value is assumed to be zero too due to the low acceptance level toward the usage of RCA and the marketability in the construction industry. The value of NA material is MYR 5.27 /t (Table 18), obtained from statistic data. Cost of diesel (Jan 2017) is MYR 2.05 (Petrolpricemalaysia, 2017).

Table 19: Summary of LCC

LCC for input and output		Unit	Cost	Notes
Machineries	Landfill compactor	MYR /t	1.05	
	Mining operation	MYR /t	4.82	
	MRF operation	MYR /t	1.18	
Transport	Truck 16-32 t (diesel)	MYR /tkm	0.12	
Wages	General worker in Landfill	MYR /t	0.0625	2 general worker in landfill, 8hr/day for MYR 50. Hourly rate is 6.25/hr. Assume that both workers managed and compacted 100 ton waste per hour. The rate is 0.0625 MYR/t of waste managed and compacted.
	General worker in MRF	MYR /t	0.3125	2 general workers in MRF 8hr/day for MYR 50. Hourly rate is 6.25/hr. Assume that both workers manual triage 20 ton waste per hour. The rate is 0.3125 MYR/t of waste triaged.
	Worker in AMQ	MYR /t	1.89	Salary paid in 2015 was 816,000,000 for 431,515,152 t of aggregate production. The rate is 1.89 MYR /t of aggregate produced.
Landfill fees	Tipping fees	MYR /t	25	
Materials	Natural aggregate	MYR /t	5.27	
	RCA	MYR /t	0	
Utilities	Electricity	MYR /kWh	3.08	Tariff F (Mining) - mining tariff for all kWh is MYR 0.381 /kWh (Source: https://www.tnb.com.my/commercial-industrial/pricing-tariffs1/)
	Diesel	MYR /L	2.05	Rate as of January 2017

**truck driver and rental costs are excluded due to lack of direct data indicating the production rate and direct working hour involve in the activities.*

7.5 Functional unit

The effective functional unit for LCA study is kg CO_2 eq /t of CW landfilled, recycled, or mined. The functional unit for LCC study is MYR /t of CW landfilled, recycled, or mined.

7.6 Results and Discussion

7.6.1 Life cycle assessment

Total GWP of the 7 case studies show a similar pattern where S1 peaked among the four scenarios. Recycling scenarios (S2, S3, and S4) show at least 37.6 % saving in project 1 and the highest emission saving of 47 % is achieved by project 6 & 7. Mining activity and truck travel distances are the main contributors to the total carbon emission. Landfill machinery emission is negliable.

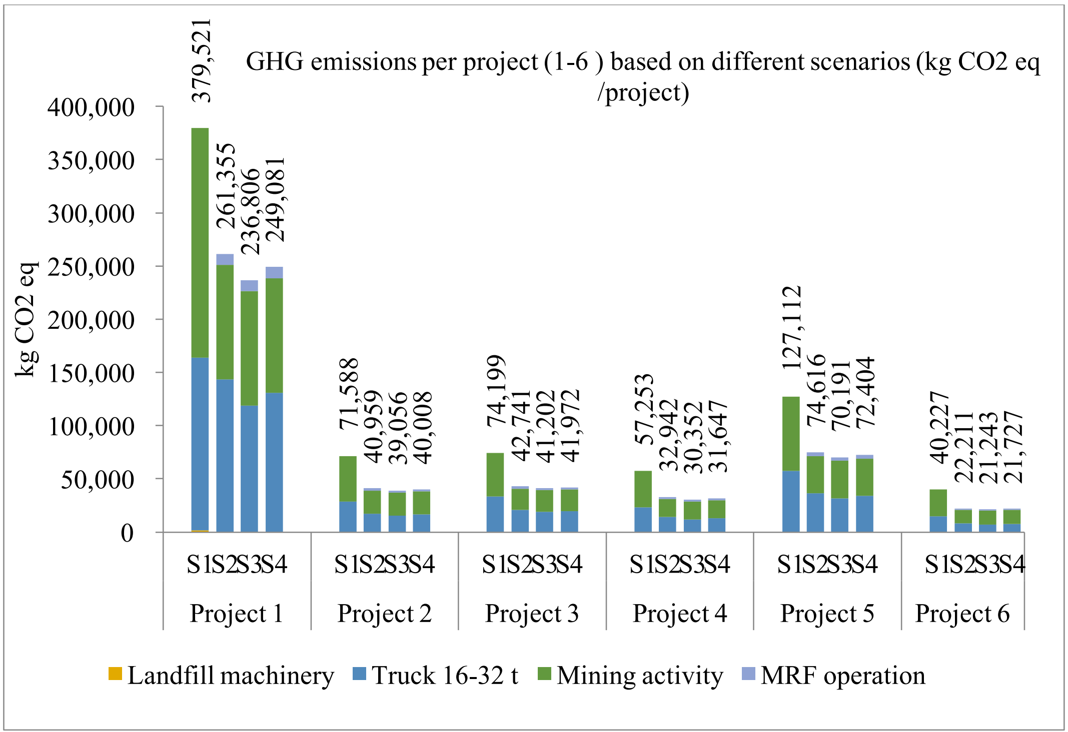

Figure 27: GHG emissions of Project 1-6 based on different scenarios (kg CO_2 eq /project)

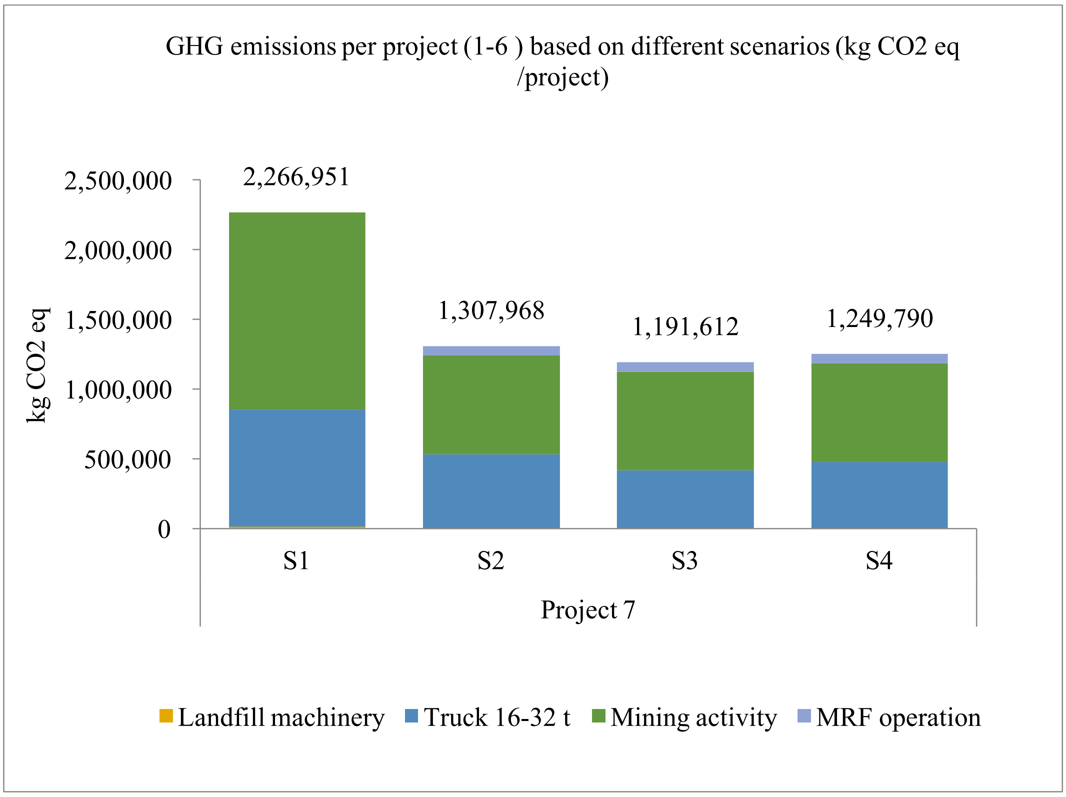

Figure 28: GHG emissions of Project 7 based on different scenarios (kg CO_2 eq /project)

S3 is among the most feasible recycling option as it emits average lesser emission per ton compared to other scenarios (Figure 28). Mining activities contributed more than 50% of the total GHG emission; it appeared to be the most relevant life cycle stage that needs further improvement. Reusing RAC is one of the options to reduce mining contribution in GHG emissions.

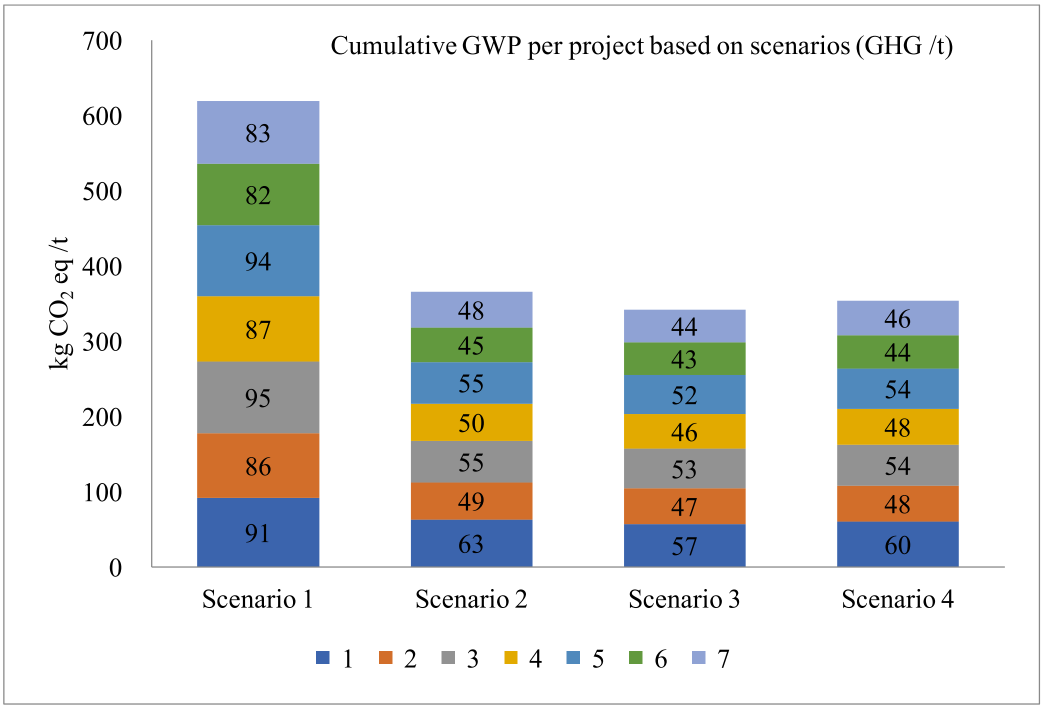

Figure 29: Cumulative GHG emissions per ton, based on 4 scenarios.

The negative values in Figure 10 indicated the saving from recycling scenarios compared to the landfilling scenario. The negative values ascertained that recycling of CW reduces environmental impact. In order to minimize the environmental impacts, CW should be recycle in MRF and reuse as road base material and also to reproduce RAC than to transporting it to landfill. The environmental benefit from substituting the NA with the RCA is the difference environmental loads between mining of NA and the recycling of CW. Recycling CW could possibly reduce the environmental impact from mining activity. Diverting the CW away from LF to recycling also reduces the amount of CW that must be landfilled.

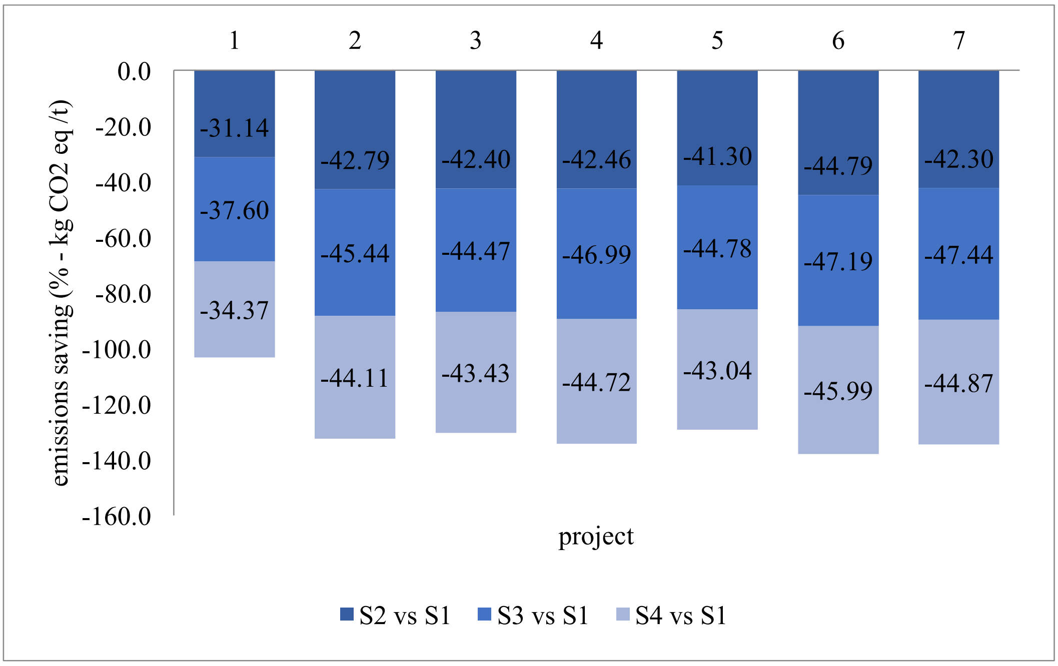

Figure 30: GHG emissions saving from recycling CW in scenario 2, 3, and 4 instead of a landfilling the CW, 7 case study projects (% kg CO_2 eq /t).

7.6.2 Life cycle costs assessment

The cost impacts from different projects show a similar trend like the LCA result where S1 peaked among the 4 scenarios. Landfilling scenario cost doubled as compared to recycling scenarios (S2, S3, and S4). Landfill tipping fees and transportation costs appeared to be the main contributors to the feasibility of the S1. In recycling scenarios, transportation is also one of the main contributors to the total cost.

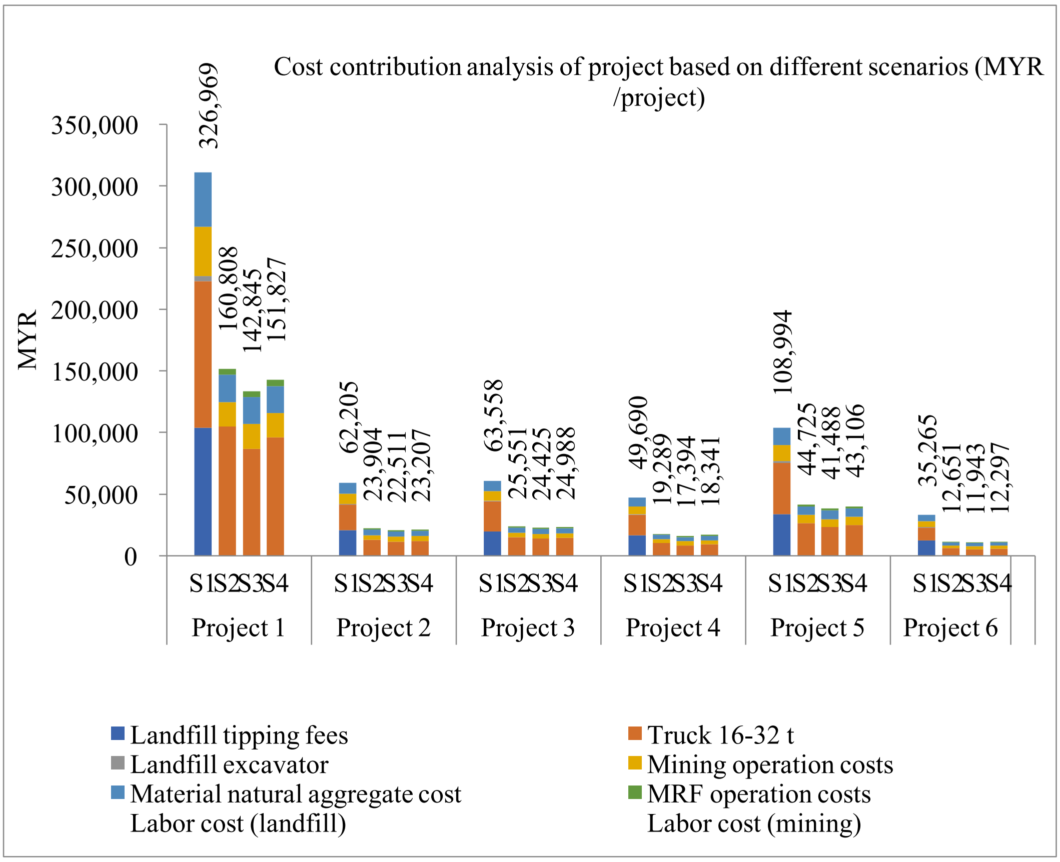

Figure 31: Cost contribution analysis of project (1-6) based on different scenarios (MYR /project)

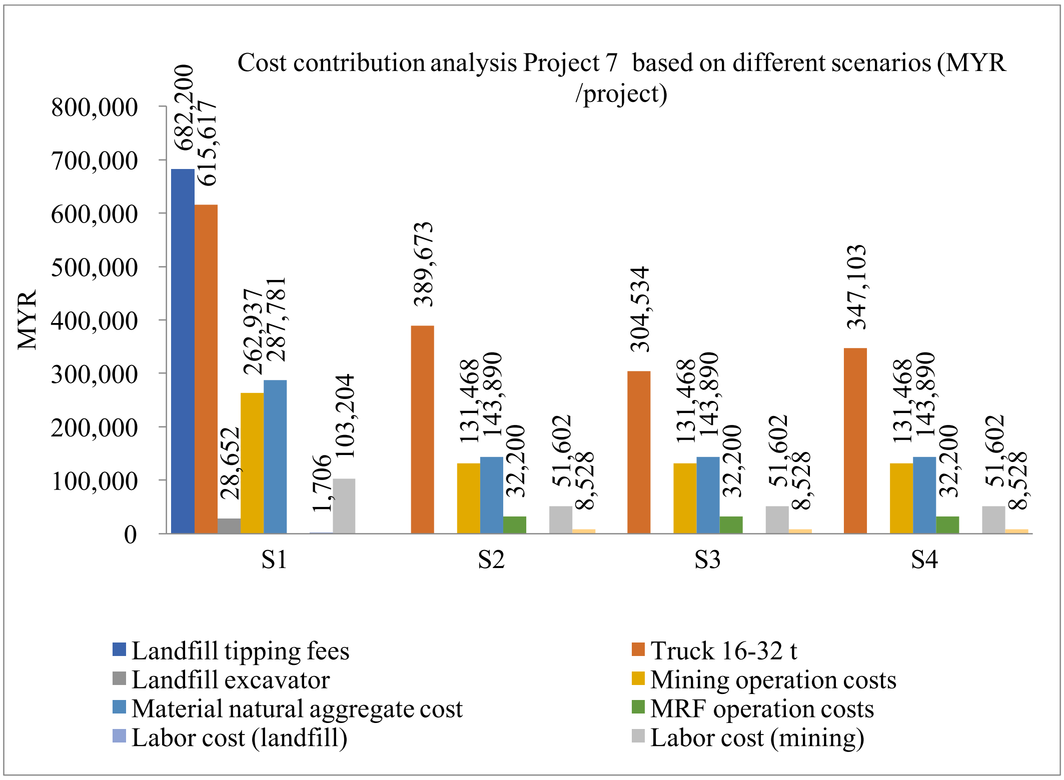

Figure 32: Cost contribution analysis of Project 7 based on different scenarios (MYR /project)

S3 is among the most feasible recycling option as it cost average lesser as compared to other scenarios (Figure 32).

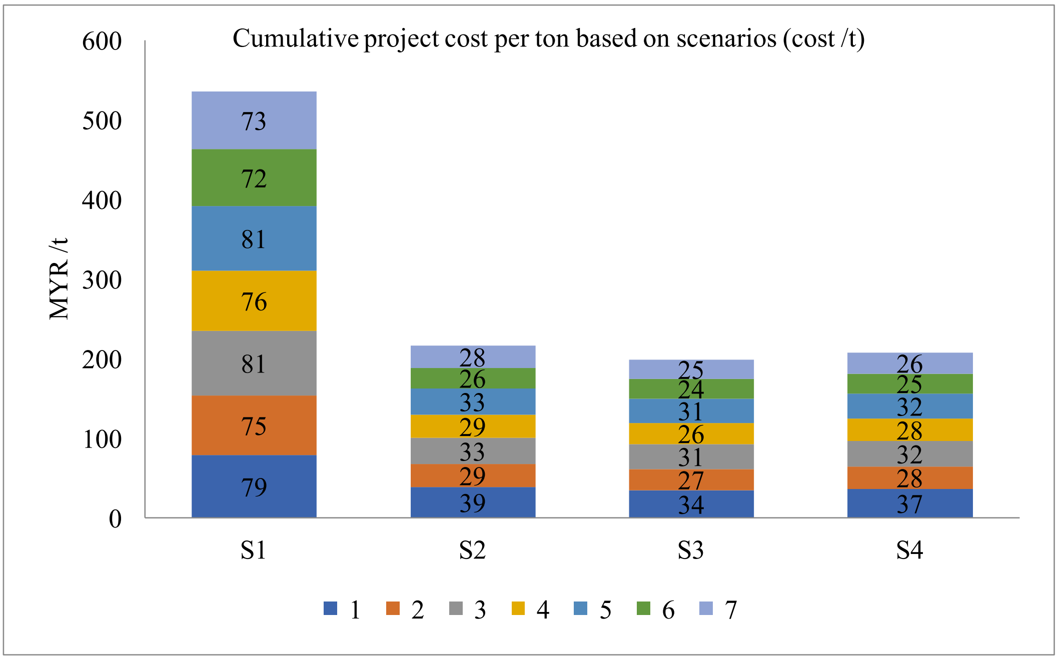

Figure 33: Cumulative project cost per ton based on 4 scenarios

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The negative values in Figure 33 indicated the saving achieved from recycling scenarios compared to the landfilling scenario. Among the recycling scenarios, recycling CW to reproduce RAC in S3 contributed to the highest cost saving. The negative values ascertained that landfilling of CW will cost more than recycling it.

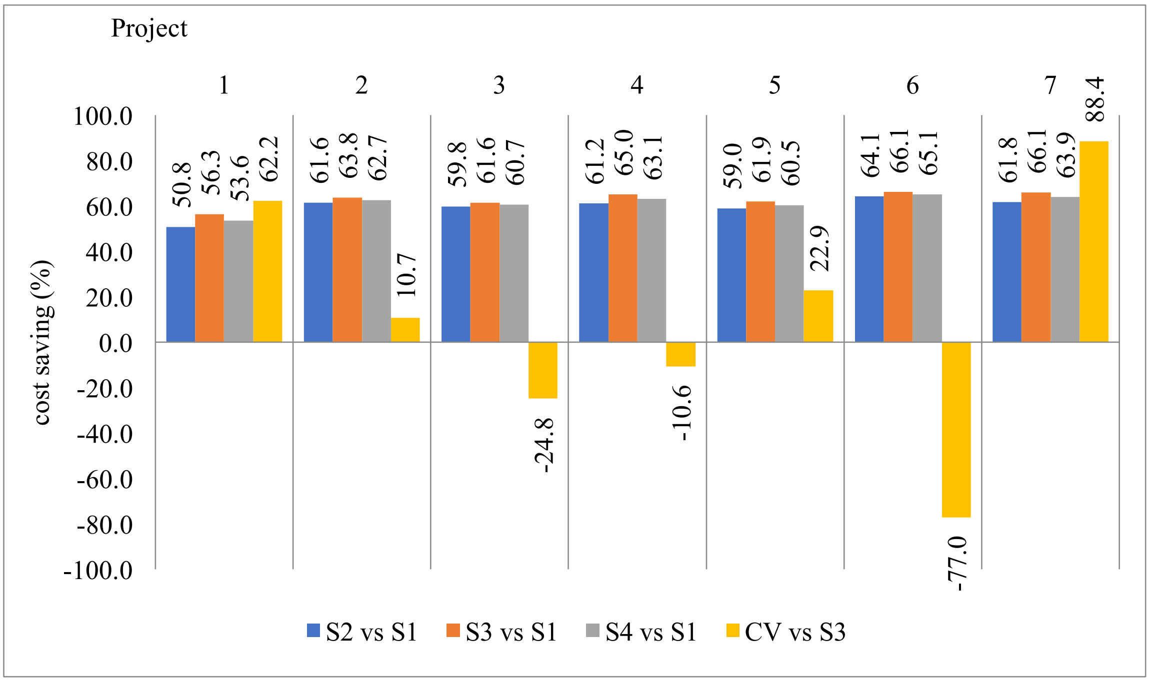

Figure 34: Cost saving from recycling CW in scenario 2, 3, 4 instead of a landfilling (S1), and contract value (CV) versus S3, for 7 case study projects (MYR /t).

With the pressing need to increase the profit margins, many developers try to minimize the cost of construction, especially in the waste management cost that has no monetary gain. In construction practice in Malaysia, it is common to have a negotiated pre-construction contract stating the budgeted or rather an estimated waste management cost. The contract value of the waste management costs of the case studies were surveyed and collected in 2016 (Table 1). The concrete contract value of waste management cost is proportionated with the CW composition of each project and recorded as a comparative parameter to the 4 scenarios (Table 7).

Table 20: Actual waste management cost versus the four scenarios

Project (MYR)	1	2	3	4	5	6	7
S1 - landfill	326,969	62,205	63,558	49,690	108,994	35,265	1,982,097
S2 - RCS	160,808	23,904	25,551	19,289	44,725	12,651	757,361
S3 - CBP	142,845	22,511	24,425	17,394	41,488	11,943	672,222
S4 - RCS & CBP	151,827	23,207	24,988	18,341	43,106	12,297	714,791
Contract value (CV)	54,000	20,093	30,479	19,238	32,000	21,141	78,014

Project 1, 2, 5, and 7 achieved a lower cost management cost through the pre-construction negotiated contract values (actual cost), which respectively cost 62.2 %, 10.7 %, 22.9 %, and 88.4 % lesser compared to the next lowest S3. In a negotiated contract, waste management contractor is paid by the developer with a lump-sum amount to manage the waste. Lump sum amount contract payment allows the developer to minimize its cost and to maximize its profit. Scrutinizing the waste management cost could have adverse effect on the waste contractor's decision and swerving it toward a cost saving measures too. For instant, illegal dumping, illegal burning or roadside dumping that has little regard on environmental impacts. The illegal options cost minimal as compared to the legal landfill. In project 3, 4, and 6 show that S3 (MYR 24,425, MYR 17,394, and MYR 11,943) is the most economical option in handling the CW. For these projects, the actual cost paid to manage the waste fall in between S1 and the S2, S3, S4 with 24.8 %, 10.6 %, and 48.6 % lesser than the cheapest S3. It is indisputable that the S1 is not an economic viable waste management solution for all of the projects. If it is a cost-based decision, then S3 will be the best choice for the entire project to recycle CW to reproduce RAC.

7.7 Sensitivity Analysis

Mining of NA activity and truck travel distances are the main contributor to GWP impact and cost impact. Generally, CS, AMQ, RCS, and CBP are usually located at a fixed location. The location of AMQ is fixed according to the natural resources and the environmental impact caused by mining activity is unavoidable, except reduction of NA material demand. In order to maximize the saving in environmental and cost impacts, mobile MRF should be build nearer to the waste producer (CS) and recycled material demand point (RCS and CBP) to offset the distance between CS to landfill.

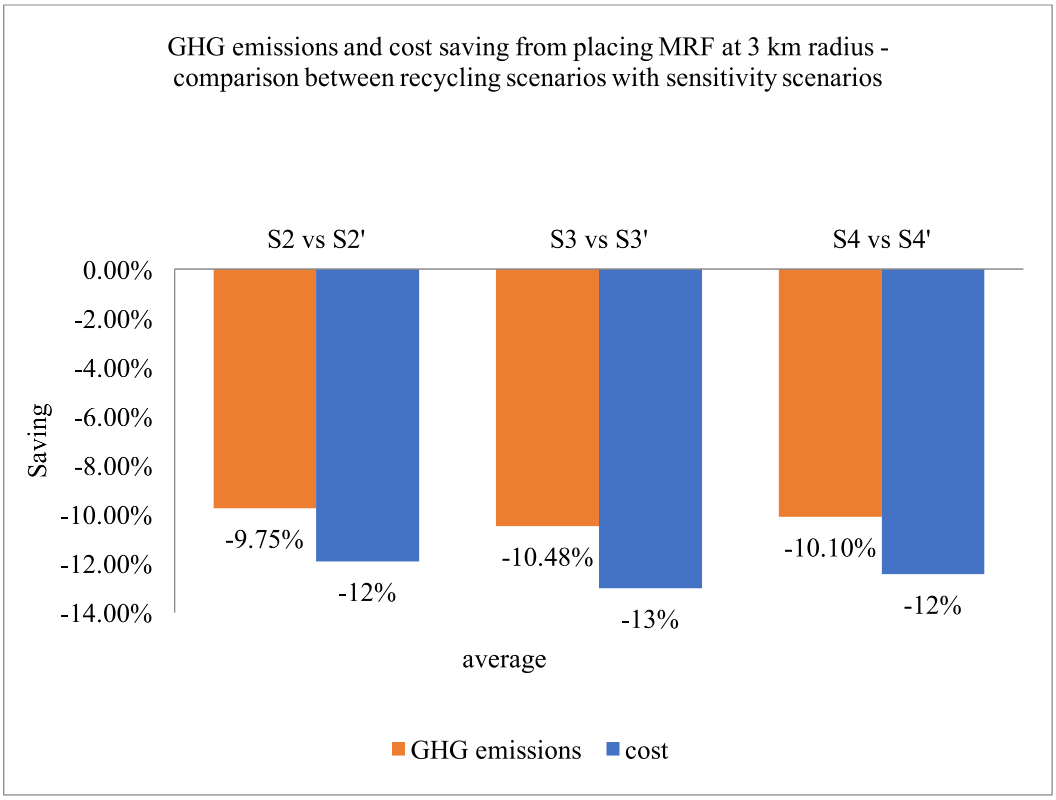

Figure 35: GHG emissions and cost saving from placing MRF at 3 km radius - comparison between recycling scenarios with sensitivity scenarios

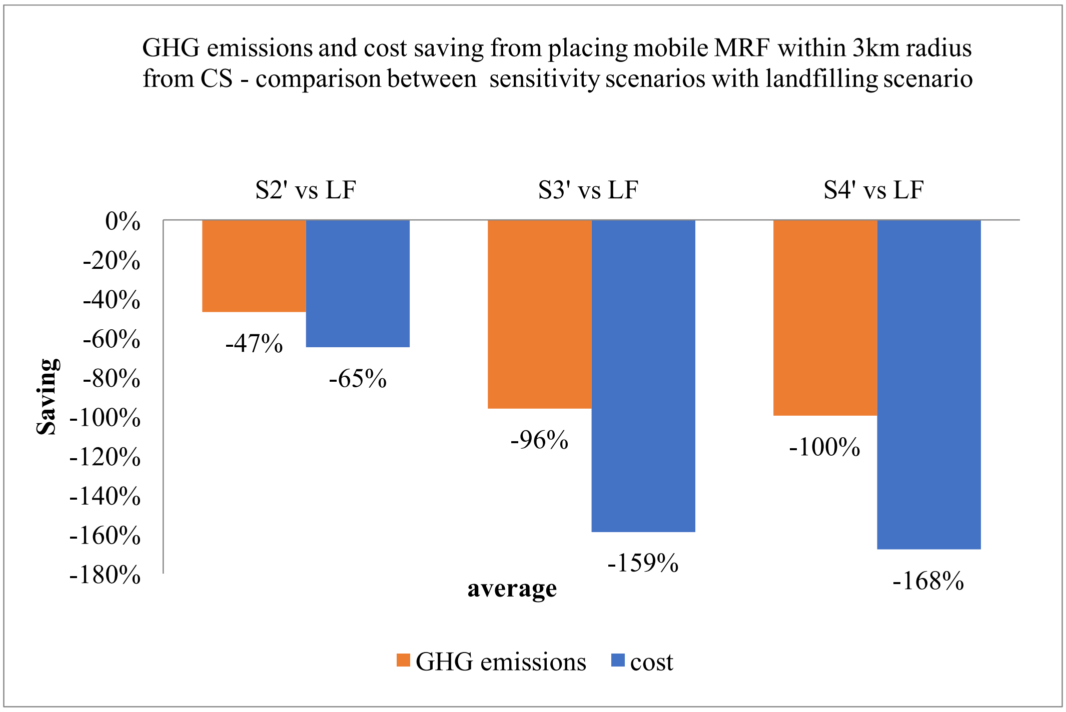

Figure 36: GHG emissions and cost saving from placing mobile MRF within 3km radius from CS - comparison between sensitivity scenarios with landfilling scenario

Figure 35 and 36 show the savings from placing a mobile MRF within 3 km radius from the CS (d_2 = 3 km). Reducing transport distances resulted in at least 9.75 – 10.48 % emission saving and 12 – 13 % of cost saving as compared to the original S2, S3, and S4 recycling scenarios (Table 15). In Table 16, at least 47 – 100 % of emissions saving and 65-168 % of cost saving could be achieved, as compared to landfilling scenario.

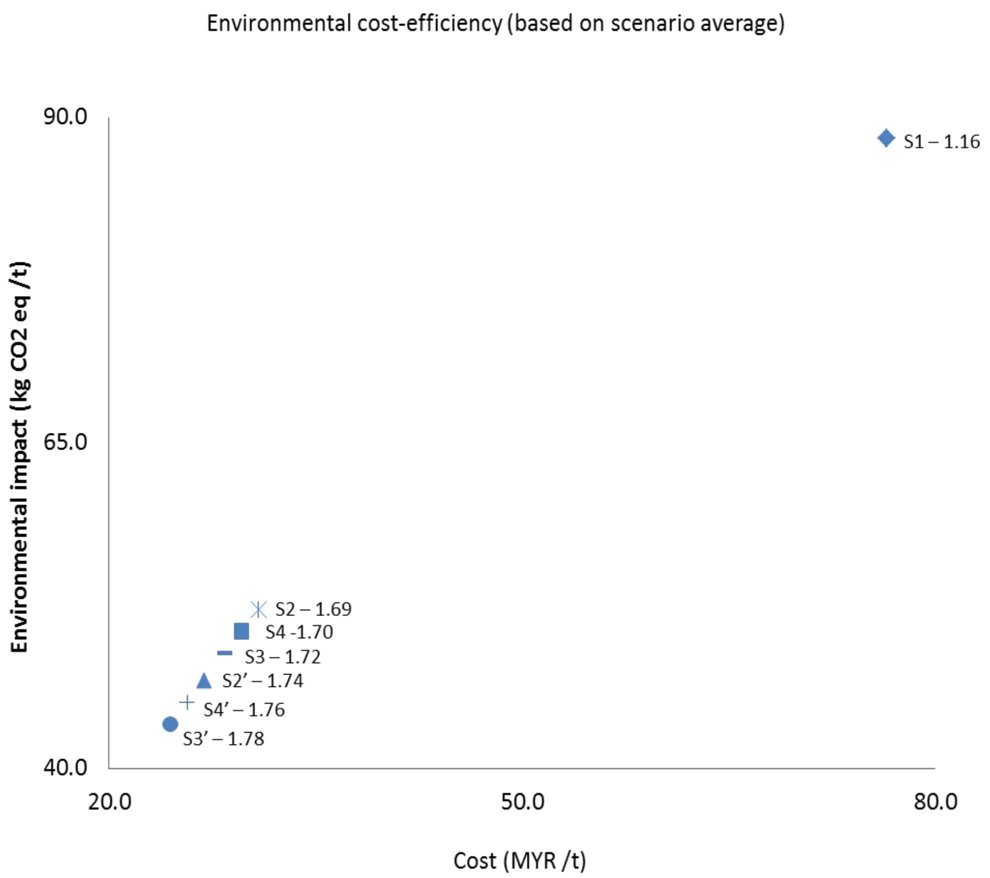

Figure 37: Environmental cost-ratio as eco-efficiency indicators

Lower left quadrant is the higher eco-efficiency area while the upper right quadrant indicated the scenario with lower eco-efficiency. If the decision has to be made considering both environmental impact and cost impact, the environmental-cost ratio graph (Figure 37) show that S2, S3, and S4 are still the best waste scenarios compared to S1 landfilling (top right quadrant). Sensitivity scenarios in reducing the travel distance to MRF show higher eco-efficiency (S2’, S3’, and S4’). Overall, CW is ideally recycled to substitute NA material. Sensitivity scenario is the most sustainable choice that emits least emission with most economical option to manage the CW.

7.8 Discussion and future study

CW remains a common constituent in landfills and illegal dumpsites, though both the environmental impact and cost impact analysis suggesting that this practice results in the lowest cost-effectiveness. Landfilling CW is environmentally unsustainable, emits average 49 % more GHG emissions and cost average 61 % more expensive compared to recycling scenarios, but it will continues until economic incentives are demonstrated to favor recycling for construction firms. It is rare that a decision must be made solely in favor of either internal firm cost interests or external environmental and social interests; rather it is generally a question of understanding and optimizing both considerations toward holistic efficiency and sustainability.

The recycling scenarios have higher eco-efficiency compared to landfilling scenario. As mentioned in the literature review, the feasibility of a waste scenario depends greatly on the transportation distances and if MRF can be build nearer to waste source and the point of demand, recycling scenarios could save up to 100 % of GHG emissions and 168 % of cost. While the centralized MRF is deemed important, adequate and consistent material throughput, facility processing capacity, recycled material markets demand, facility ownership and operation are among the various factors that influence the sustainability of waste recycling industry. The concrete industry has achieved advancement in developing RAC, yet it made no significant gains in reducing the GHG emissions in concrete industry as compared to the cement (Portland cement) production. The current economic disadvantages and industry practice in waste management are enough to outweigh any environmental impacts saving that may be added to any project. Sorting the mixture of construction and demolition waste into CW is not an easy process. The unknown constituent of reinforced steel, glass, or wood attached in CW could further affect the recovery feasibility. Even though the study concluded that RAC generally produced lesser GHG emissions with lower cost impact, the practicality of applying RAC in structural component still needs further research. Recovery and recycling of CW is sufficiently proven in this study to have positive environmental cost-effectiveness.

In order to align decision making with the most environmental sound waste management scenario, a holistic waste management scenario must allow the decision maker to overcome its transaction costs or at least minimize its losses. A contractor will pursue recycling only where its direct economic benefits outweigh landfilling, regardless of costs to externalize to the environment. Institutional support could make the recycling option into a workable CW management option. Intervening forces, such as government and regulatory policy and enforcement, may modify the economic incentives, and thus the contractor’s decision making process to promote recycling over landfilling. Recycling tax incentives to a company that recycles is the most common stimulant to shift the decision making paradigm from landfilling to the recycling. Policy makers could also impose coercive policies such as carbon tax, waste tax penalization to shift economic costs directly to those rendering the environmental impacts. Reduction in overall CW emissions requires specific studies of optimal material recycling facility locations. Such optimization studies should follow this study's use of real transportation distances, rather than general assumptions, to improve the real world applicability.

7.8.1 Optimal location to build material recovery facilities

Way forward to find the optimal location for mobile MRF – to minimize environmental impacts and minimize recycling cost. From the result, the emissions from transportation contribute a significant fluctuation to the feasibility of the waste scenarios. In the concrete waste chain network, the concrete waste is collected, processed, and dispersed from MRF to the end-users. The location of MRF is view as the most critical factors in influencing the feasibility of a certain waste scenario, should be strategically and centrally located in between the supply and demand nodes. A centrally located MRF will reduce the travel distances and cost of transportation that could reduce the overall environmental impacts and increase the economic feasibility of recycling concrete waste.

Thus, this study proposed a way forward in optimizing the location of the MRF considering the minimization of the carbon emission. The goal of the optimization is to find out the optimal location to build a new mobile MRF that satisfy the lowest carbon emission and lowest waste management cost.

Let's imagine the construction site (core area) is within the radius (R) km, and the location is an original point with the coordinate of (0, 0) of a polar coordination system. The undefined location of MRF is expressed as *PMRF* (α, β), where α is a distance from the original point and β is an angle from the line beaming from the original point to the east. Weight transport (t.km) of CD waste from CS to MRF is denoted as the following Eq. 2. The function *dist* (A, B) means the distance (km) between location A and location B.

$$T_{CS,MRF}(\alpha,\beta) = W\ dist\big(P_{CS}, P_{MRF}(\alpha,\beta)\big) \quad (2)$$

In the scenario 3, assume that half of CW is transported to RCS and the other half is to CBP.

In general assumption, assume that the road construction activity is a radial diagram. The road construction activity is presuming to be higher at the center (city center or core area) of construction site and reduce gradually toward the edge of the radial diagram.

To simplify, assume the demand of RCA is X (t) amount by the road construction site. The density function of CW $d_{RCS}(r, \theta)$ is defined as in Eq. 3. It has the following constraint.

$$1 = \int_0^R \int_0^{2\pi} d_{RCS}(r,\theta) d\theta dr \tag{3}$$

By using the density function, weight transportation of RCA to RCS is described as,

$$T_{MRF,RCS}(\alpha,\beta) = \frac{W}{2} \int_0^R \int_0^{2\pi} dist\big(P_{MRF}(\alpha,\beta), P_{RCS}(r,\theta)\big) d_{RCS}(r,\theta) d\theta dr \tag{4}$$

Weight transportation of RAC to CBP is denoted as,

$$T_{MRF,CBP}(\alpha,\beta) = \frac{W}{2} dist(P_{MRF}(\alpha,\beta), P_{CBP}) \tag{5}$$

Since (X- W/2) (t), the remaining part of virgin aggregate demanded by the RCS and is supplied by AMQ, the weight transportation of that is expressed in Eq. 6,

$$T_{AMQ,RCS} = \left(X - \frac{W}{2}\right) \int_0^R \int_0^{2\pi} dist\left(P_{AMQ}, P_{RCS}(r,\theta)\right) d_{RCS}(r,\theta) d\theta dr \tag{6}$$

Aggregate mining quarry (AMQ) supplies (Y- W/2) (t) of virgin aggregate to CBP so that CBP can produces the same amount of output (product) as in BAU case.

$$T_{AMQ,CBP} = \left(Y - \frac{W}{2}\right) dist\big(P_{AMQ}, P_{CBP}\big) \tag{7}$$

The total of weight transportation for S3 is described as in Eq. 8,

$$T_{all}(\alpha,\beta) = T_{CS,RMF}(\alpha,\beta) + T_{RMF,RCS}(\alpha,\beta) + T_{RMF,CBT}(\alpha,\beta) + T_{ANQ,RCS} + T_{ANQ,CBT} \tag{8}$$

To find the optimal MRF location (α, β) that satisfies the following minimization.

$$\min_{\alpha,\beta}\{T_{CS,RMF}(\alpha,\beta) + T_{RMF,RCS}(\alpha,\beta) + T_{RMF,CBT}(\alpha,\beta)\} \tag{9}$$

To simplify the explanation, three assumptions are introduced: 1) location of MRF is out of construction area, 2) use a single variable function of distance *r* as the demand density, and 3) use point-to-point strait-line distance instead of road distance. The MRF is ideally located at the point where it is convenient for CDW collection and distribution to the RCS area. Ideally the MRF should be built on the same site as CS to minimize the carbon emission generated from transportation. Due to the circumstances as such; land scarcity or difficulties in planning for site logistic and transportation, building a MRF in the CS is highly unlikely to happen. Therefore, the MRF is preferred to be located at the boundary of the CS, so that, $\alpha=R$.

From the assumption 2), the demand density can be described as,

$$d_{RCS}(r,\theta) = f(r), \quad r \leq R \tag{10}$$

Using this demand density and assumption 3), the weight transportation from MRF to RCS becomes a constant at any angle β. (See Appendix 1)

$$T_{MRF,RCS}(R,\beta) = const\ at\ any\ \beta \tag{11}$$

As the result, the optimal location of MRF that satisfied Eq. (9) is the cross point of the radial boundary of CS and that is the shortest path between CS and CBP.

If the demand density does not satisfy Eq. (10), the optimal location of MRF will shift from the cross point but still located on the radial boundary. For instant, when the highway or trunk road between CS and another city is constructed, the demand density loses the property of center symmetry. Consequently, the optimal location for MRF shifts from the cross point.

In future studies, the calculation of LCA calculation will be conducted in the condition that MRF is at the cross point.

Using strait-line distance, the distance function in Eq. (4) is expressed,

$$dist\big(P_{RMF}(\alpha,\beta), P_{RCS}(r,\theta)\big) = \sqrt{(\alpha\ sin\beta - r\ sin\theta)^2 + (\alpha\ cos\beta - r\ cos\theta)^2} = \sqrt{(\alpha^2 + r^2) - 2\alpha r\ cos(\beta - \theta)} \tag{A1}$$

Using simplified demand density function in Eq. (10), Eq. (4) is,

$$T_{RMF,RCS}(\alpha,\beta) = \frac{W}{2}\int_0^R \int_0^{2\pi} \sqrt{(\alpha^2 + r^2) - 2\alpha r\, cos(\beta - \theta)} f(r) d\theta dr \tag{A2}$$

For θ, substitute $\psi+(\beta-\gamma)$, ($\gamma<>\beta$) in Eq.(A2), then,

$$T_{RMF,RCS}(\alpha,\beta) = \frac{W}{2}\int_0^R \int_0^{2\pi} \sqrt{(\alpha^2 + r^2) - 2\alpha r\, cos(\gamma - \psi)} f(r) d\psi dr = T_{RMF,RCS}(\alpha,\gamma) \tag{A3}$$

Therefore, $T_{RMF,RCS}(\alpha,\beta)$ is constant at any β.

7.9 Summary and Conclusion

The main outcome of this study highlighted the importance of concrete waste recycling towards achieving higher eco-efficiency, to reduce the environmental impact and to reduce cost associated in landfilling concrete waste (CW). Concrete waste is preferably uses as a substitution of the natural aggregates to reduce the impacts from mining activities and production of new raw material.

The integration of economic and environmental parameters is important to explicitly recognize the contribution of economic impact in influencing the environmental sound decision making. This study analyzed the industry's actual decision-making regarding CW management costs and practices. It is useful for researchers, industry decision makers, and also environmental economists to incorporate such cost impacts when recommending sustainable waste management plan.

References

Biswas, W. K. (2014). Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia. The International Journal of Life Cycle Assessment, 19(4), 732-744.

Bovea, M. D., & Powell, J. C. (2016). Developments in life cycle assessment applied to evaluate the environmental performance of construction and demolition wastes. Waste Management, 50, 151-172.

Butera, S., Christensen, T. H., & Astrup, T. F. (2015). Life cycle assessment of construction and demolition waste management. Waste Management, 44, 196-205.

Carlsson Reich, M. (2005). Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). Journal of Cleaner Production, 13(3), 253-263.

Cement Association of Canada, C. (2016). Concrete Design Handbook – 4th Edition (4th ed.). Toronto, Canada.

Consonni, S., Giugliano, M., & Grosso, M. (2005). Alternative strategies for energy recovery from municipal solid waste. Waste Management, 25(2), 137-148.

Department of Statistic, M. (2012-2015). Quarterly construction statistics. Department of Statistics Malaysia Retrieved from https://newss.statistics.gov.my/newss-portalx/ep/epProductFreeDownloadSearch.seam (accessed December 20, 2015)

Department of Statistic, M. (2016). Economic cencus 2016 - Mining and quarrying. Department of Statistics Malaysia Retrieved from https://www.dosm.gov.my/v1/index.php?r=column/cthemeByCat&cat=97&bul_id=dVE3UXhFcVkzTFVPVXVWNkt6NDlpUT09&menu_id=TXdvYTlvQXVlTFhVOUJ6NVVESVBNUT09 (accessed July 20, 2017)

Duan, H., & Li, J. (2016). Construction and demolition waste management: China's lessons. Waste Management & Research, 34(5), 397-398.

EU, E. U. (2011). Supporting Environmentally Sound Decisions for Construction and Demolition (C&D) Waste Management. from Italy: http://eplca.jrc.ec.europa.eu/uploads/waste-Guide-to-LCTLCA-for-C-D-waste-management-Final-ONLINE.pdf (accessed

ISO14040. (2006). Environmental management — Life cycle assessment — Principles and framework.

ISO14044. (2006). Environmental management — Life cycle assessment — Requirements and guidelines.

Kloepffer, W. (2008). Life cycle sustainability assessment of products. The International Journal of Life Cycle Assessment, 13(2), 89.

Lachimpadi, S. K., Pereira, J. J., Taha, M. R., & Mokhtar, M. (2012). Construction waste minimisation comparing conventional and precast construction (Mixed System and IBS) methods in high-rise buildings: A Malaysia case study. Resources, Conservation and Recycling, 68(0), 96-103.

Ma, F., Sha, A., Yang, P., & Huang, Y. (2016). The Greenhouse Gas Emission from Portland Cement Concrete Pavement Construction in China. International Journal of Environmental Research and Public Health, 13(7), 632.

Mah, C. M., Fujiwara, T., & Ho, C. S. (2016). Construction and Demolition Waste Generation Rates For High-Rise Buildings in Malaysia. Waste Management & Research.

Mah, C. M., Fujiwara, T., & Ho, C. S. (2017). Concrete Waste Management Decision Analysis Based On Life Cycle Assessment. Chemical Engineering Transactions, 56.

Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. Waste Management, 30(11), 2255-2264.

Marinković, S. B., Ignjatović, I., & Radonjanin, V. (2013). 23 - Life-cycle assessment (LCA) of concrete with recycled aggregates (RAs) A2 - Pacheco-Torgal, F. In V. W. Y. Tam, J. A. Labrincha, Y. Ding, & J. d. Brito (Eds.), Handbook of Recycled Concrete and Demolition Waste (pp. 569-604): Woodhead Publishing.

Martinez-Sanchez, V., Kromann, M. A., & Astrup, T. F. (2015). Life cycle costing of waste management systems: Overview, calculation principles and case studies. Waste Management, 36, 343-355.

Mercante, I. T., Bovea, M. D., Ibáñez-Forés, V., & Arena, A. P. (2012). Life cycle assessment of construction and demolition waste management systems: a Spanish case study. The International Journal of Life Cycle Assessment, 17(2), 232-241.

MLIT. (2014). White Paper on Land, Infrastructure, Transport and Tourism in Japan 2014. Japan: Ministry of Land Infrastructure Transport and Tourism, MLIT Retrieved from http://www.mlit.go.jp/common/001063075.pdf (accessed 01.10.2016)

NEA. (2016). Waste statistics and overall recycling. Singapore: National environment agency Retrieved from http://www.nea.gov.sg/energy-waste/waste-management/waste-statistics-and-overall-recycling (accessed

Ondova M., S. N. (2013). Environmental assessment of fly ash concrete. Chemical Engineering Transactions, 35, 841-846.

Petrolpricemalaysia (2017) Petrol price in Malaysia. From Publications http://petrolpricemalaysia.info/ (accessed

Rigamonti, L., Grosso, M., & Sunseri, M. C. (2009). Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems. The International Journal of Life Cycle Assessment, 14(5), 411-419.

Ristimäki, M., Säynäjoki, A., Heinonen, J., & Junnila, S. (2013). Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. Energy, 63, 168-179.

Rosado, L. P., Vitale, P., Penteado, C. S. G., & Arena, U. (2017). Life cycle assessment of natural and mixed recycled aggregate production in Brazil. Journal of Cleaner Production, 151, 634-642.

Tošić, N., Marinković, S., Dašić, T., & Stanić, M. (2015). Multicriteria optimization of natural and recycled aggregate concrete for structural use. Journal of Cleaner Production, 87, 766-776.

UNCRD. (2015). 3R as an economic industry - next generation 3r solutions for a resource efficient society and sustainable tourism development in asia and the pacific. Paper presented at the Sixth Regional 3R Forum in Asia and the Pacific, Malé, Maldives, 9-10,United nations centre for regional development

Zealand, C. C. C. A. o. N. (2011). Recycled Aggregates in New Concrete. from New Zealand: www.ccanz.org.nz/files/documents/ad659c71-06cb-44b1-95dd-7b7350fdcd54/TR_14_Recycled_Aggregates_in_New_Concrete_2013.pdf (accessed 07.07.2016)

8 Life cycle assessment of mixed C&DW

8.1 Introduction

C&DW is usually discharged without separation. Poon, Yu, and Ng (2001) study mentioned that the construction participants are reluctant to carry out on-site waste sorting even when high a tipping fee is imposed. C&DW sorting on-site is considered as a time consuming and labor intensive activity which construction participants will try to avoid. In Malaysia, on-site waste separation is rare except those C&DW materials that yield a higher resell value.

The main objective of this chapter is to access the environmental impacts with different waste disposal scenarios of mixed C&DW materials. This chapter study focused on waste disposal scenarios, the end-of-life stage that were designed according to the waste management hierarchy of reduce, recycle, incineration with energy recovery, and finally landfill (Figure 40). In waste disposal scenario, the assessment excluded the embodied impacts from assemble, production, and use phases. The 'reuse' scenarios for all C&DW material is not modelled due to the usage of C&DW materials vary greatly between projects that make it difficult to cut off the system boundary.

Mixed C&DW materials consisted of 10 categories, brick, cement, concrete, gypsum, packaging, paper, and board, reinforced concrete, sand soil dirt, scrap metal, tiles, timber, and plywood. Packaging, paper, and board are disposed to municipal solid waste landfill instead of inert landfill. It is assumed that other C&DW materials were sent to inert landfill (Table 23).

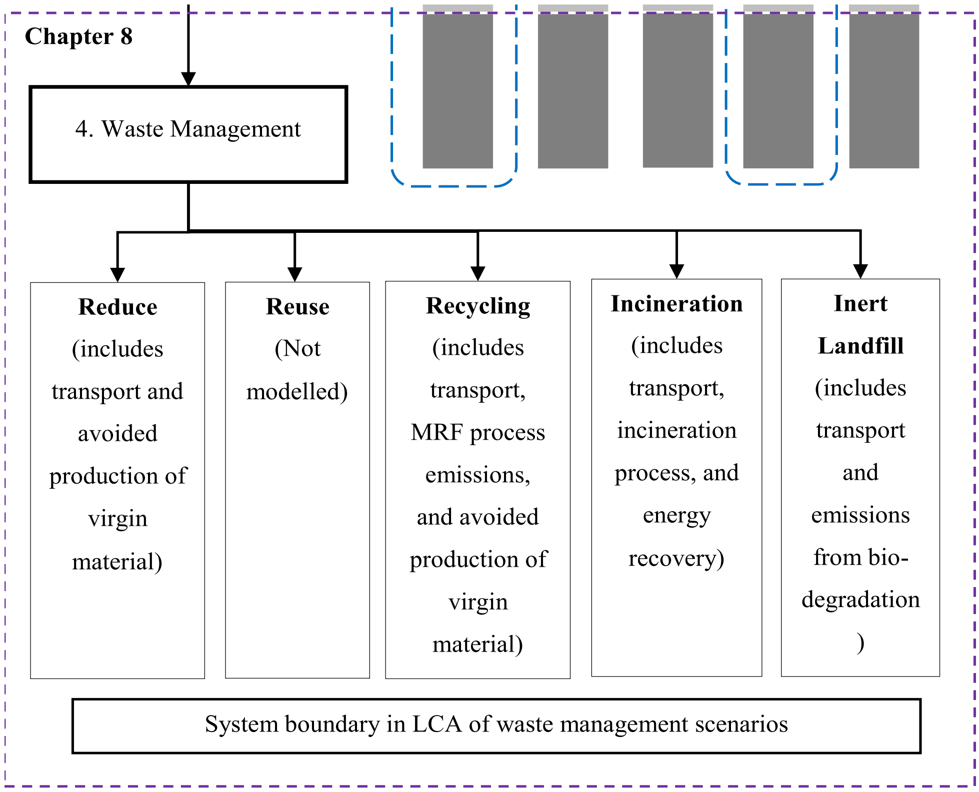

Figure 38: System boundaries of mixed C&DW scenarios in Chapter 8

This chapter is presented in a few sections. Life cycle inventories data that were collected and presented in Chapter 3 and 4 were used as the input data to waste management scenarios. Life cycle inventories analysis (LCIA) is presented in section two of this chapter, describes the functional unit of life cycle emissions of reducing 1 ton of C&DW, recycling 1 ton of C&DW, and landfilling 1 ton of C&DW. The inputs that are included in this study are listed in Table 21 and the emissions and impacts assessment are listed in Table 22.

Table 21: LCI Inputs

Electricity usage in MRF
Fuel consumption for transportation
Travel distance
Landfill machinery

Table 22: List of Outputs included in LCI

		unit
Selected LCI results	Sulphur dioxide	kg SO_2 eq
	Nitrogen oxides	kg NO_x eq
	Total particulates <2.5um	kg PM
	Land occupation	m^2a
IPCC GWP 100a	GWP	kg CO_2 eq
Recipe Endpoint	Human Health	DALY
	Ecosystems	Species.yr
	Resources	$

The intended audience of this chapter is to allow the communication between all the stakeholders involve in C&DW management, for instance, the waste manager (contractor), the waste generator (developers), the waste operator (landfill manager, incinerator manager, material recovery facility manager, and etc.), and finally the policy makers (government). The interpreted results from this chapter are intended to help to make a more informed decision based on comparative studies on cradle-to-grave, cradle-to-cradle scenarios in C&DW management industry.

8.2 Life Cycle Inventories Analysis

Life cycle inventories data of C&DW materials were extracted from Simapro ecoinvent database. Waste material flow is modelled with using Simapro software and the environmental impacts values were extracted according to different disposal scenarios. In life cycle assessment, the environmental impact assessment was performed with endpoint indicators with the damage assessment method, ReCiPe. The Intergovernmental Panel on Climate Change, Global warming potential (IPCC GWP 100a), expressed the amount of carbon dioxide trapped in the atmosphere was measured and recorded over 100-year span.

The distances between CS - LF is 60.9 km and CS - MRF is 36.1 km (the average distance from 7 case studies). The distance between CS - incinerator is assumed at 50 km.

8.3 Results of life cycle inventories analysis

The negative values represent an advantage in the environment impact category because it represents the emissions avoided.

Table 23: Life cycle emissions from reducing 1 t of mixed C&D waste

Reduce	Carbon oxide kg CO	Sulphur dioxide kg SO_2	Nitrogen oxides kg NO_x	Total particulates <2.5um kg PM	Land occupation m^2a	GWP kg CO_2 eq	Human Health DALY	Ecosystems Species.yr	Resources $
Brick	-0.000696	-0.000465	-0.000576	-0.0000959	-0.0215	-0.247	-0.00000047	-2.32E-09	-0.00976
Cement	-1.94	-1.24	-1.08	-0.261	-36.7	-536	-0.00106	-4.81E-06	-19.6
Concrete	-0.342	-0.291	-0.546	-0.0844	-7.01	-247	-0.000455	-2.17E-06	-6.42
Gypsum	-0.00288	-0.0189	-0.0044	-0.000326	-	-3.03	-0.0000066	-2.38E-08	-0.17
Packaging paper board	-1.16	-1.77	-1.39	-0.463	-532	-612	-0.00137	-0.0000125	-33.3
Reinforced concrete	-7.55	-0.324	-0.869	-0.0281	-2.4	-707	-0.00114	-5.68E-06	-28.5
Sand soil dirt	-0.000086	-0.000109	-0.000118	-0.000018	-0.00301	-0.0289	-6.49E-08	-2.96E-10	-0.00136
scrap metal	-1.39	-4.44	-1.32	-0.821	-50.9	-385	-0.00354	-3.93E-06	-85.7
Tiles	-1.81	-3.37	-1.92	-9.56	-96	-1090	-0.00465	-0.0000104	-61
Timber plywood	-6.04	-1.91	-2.35	-1.26	-4380	-532	-0.00162	-0.0000581	-34
Total	-20.24	-13.36	-9.48	-12.48	-5105.03	-4112.31	-0.0138	-9.762E-05	-268.70

Table 24: Life cycle emissions of recycling 1 t of mixed C&D

Recycle	Carbon oxide kg CO	Sulphur dioxide kg SO_2	Nitrogen oxides kg NO_x	Total particulates <2.5um kg PM	Land occupation m^2a	GWP kg CO_2 eq	Human Health DALY	Ecosystems Species.yr	Resources $
Brick	0.0263	0.0239	0.0569	0.0277	0.706	12.7	0.0000493	1.13E-07	0.767
Cement	0.0319	0.0299	0.0645	0.0267	1.22	14.6	0.0000567	1.26E-07	0.921
Concrete	0.025	0.0229	0.0593	0.0278	0.514	12.5	0.000049	1.16E-07	0.728
Gypsum	0.0241	0.0236	0.0313	0.00875	1.24	10.8	0.0000238	7.87E-08	0.755
Packaging paper board	0.0507	0.0384	0.0854	0.0167	2.09	17.5	0.0000498	1.19E-07	1.19
Reinforced concrete	0.038	0.0299	0.0624	0.0169	1.7	13.9	0.0000375	9.19E-08	1.02
Sand soil dirt	0.0411	0.0319	0.0557	0.0115	2.2	13.8	0.0000309	7.57E-08	1.1
scrap metal	0.0126	0.0235	0.0169	0.00995	0.68	10.4	0.000023	1.00E-07	0.583
Tiles	0.0411	0.0319	0.0557	0.0115	2.2	13.8	0.0000309	7.57E-08	1.1
Timber plywood	0.0271	0.0605	0.0413	0.025	1.79	21.9	0.0000503	2.01E-07	1.12
Total	0.3179	0.3164	0.5294	0.1825	14.34	141.9	0.0004012	1.097E-06	9.284

Table 25: Life cycle emissions of incinerate 1 t of mixed C&D

Incinerate	Carbon oxide kg CO	Sulphur dioxide kg SO_2	Nitrogen oxides kg NO_x	Total particulates <2.5um kg PM	Land occupation m^2a	GWP kg CO_2 eq	Human Health DALY	Ecosystems Species.yr	Resources $
Packaging paper board	0.133	0.07	0.32	0.0172	1.51	41.3	0.000176	3.79E-07	1.53
scrap metal	0.155	0.0841	0.33	0.0216	2.5	527	0.00105	4.55E-06	1.91
Timber plywood	0.274	0.0322	0.376	0.0154	0.899	17.8	0.0000882	1.68E-07	1.05
Total	0.562	0.1863	1.026	0.0542	4.909	586.1	0.0013142	5.097E-06	4.49

Table 26: Life cycle emissions of landfill 1 t of mixed C&D

Landfill	Carbon oxide	Sulphur dioxide	Nitrogen oxides	Total particulates <2.5um	Land occupation	GWP	Human Health	Ecosystems	Resources
	kg CO	kg SO_2	kg NO_x	kg PM	m^2a	kg CO_2 eq	DALY	Species.yr	$
Brick	0.0656	0.04	0.113	0.0325	2.69	21.8	7.02E-05	1.56E-07	1.62
Cement	0.0467	0.0298	0.0575	0.0102	2.40	15.4	3.38E-05	9.52E-08	1.23
Concrete	0.0467	0.0298	0.0575	0.0102	2.40	15.4	3.38E-05	9.52E-08	1.23
Gypsum	0.0467	0.0298	0.0575	0.0102	2.40	15.4	3.38E-05	9.52E-08	1.23
Packaging paper board (Inert LF)	0.0998	0.145	0.136	0.0421	6.10	1370	1.68E-03	0.00000876	2.14
Reinforced concrete	0.0467	0.0298	0.0575	0.0102	2.40	15.4	3.38E-05	9.52E-08	1.23
Sand soil dirt	0.0467	0.0298	0.0575	0.0102	2.40	15.4	3.38E-05	9.52E-08	1.23
scrap metal	0.0467	0.0298	0.0575	0.0102	2.40	15.4	3.38E-05	9.52E-08	1.23
Tiles	0.0467	0.0298	0.0575	0.0102	2.40	15.4	3.38E-05	9.52E-08	1.23
Timber plywood (Inert LF)	0.0858	0.0974	0.121	0.032	5.9	637	1.06E-03	0.0000043	1.98
Total (Inert + MSW LF)	0.5781	0.491	0.7725	0.178	31.49	2136.6	0.0030468	1.3882E-05	14.35

Reduce is the first preference in waste management hierarchy and reducing 1 ton of mixed C&DW shows positive avoided impacts, which suggested that reducing is always a better choice compared to landfilling.

Table 27: Emission savings from reducing 1 t of mixed C&D waste in MRF instead of landfilling

Reduce - Landfill	Carbon oxide kg CO	Sulphur dioxide kg SO_2	Nitrogen oxides kg NO_x	Total particulates <2.5um kg PM	Land occupation m^2a	GWP kg CO_2 eq	Human Health DALY	Ecosystems Species.yr	Resources $
Brick	-0.066296	-0.040465	-0.113576	-0.0325959	-2.7115	-22.047	-7.07E-05	-1.583E-07	-1.62976
Cement	-1.9867	-1.2698	-1.1375	-0.2712	-39.1	-551.4	-0.001094	-4.905E-06	-20.83
Concrete	-0.3887	-0.3208	-0.6035	-0.0946	-9.41	-262.4	-0.000489	-2.265E-06	-7.65
Gypsum	-0.04958	-0.0487	-0.0619	-0.010526	-2.4	-18.43	-4.04E-05	-1.19E-07	-1.4
Packaging paper board	-1.2598	-1.915	-1.526	-0.5051	-538.1	-1982	-0.00305	-2.126E-05	-35.44
Reinforced concrete	-7.5967	-0.3538	-0.9265	-0.0383	-4.8	-722.4	-0.001174	-5.775E-06	-29.73
Sand soil dirt	-0.046786	-0.029909	-0.057618	-0.010218	-2.40301	-15.4289	-3.39E-05	-9.55E-08	-1.23136
scrap metal	-1.4367	-4.4698	-1.3775	-0.8312	-53.3	-400.4	-0.003574	-4.025E-06	-86.93
Tiles	-1.8567	-3.3998	-1.9775	-9.5702	-98.4	-1105.4	-0.004684	-1.05E-05	-62.23
Timber plywood	-6.1258	-2.0074	-2.471	-1.292	-4385.9	-1169	-0.00268	-0.0000624	-35.98
Total	-20.813762	-13.855474	-10.252594	-12.6559399	-5136.52451	-6248.9059	-0.016889	-0.0001115	-283.05112

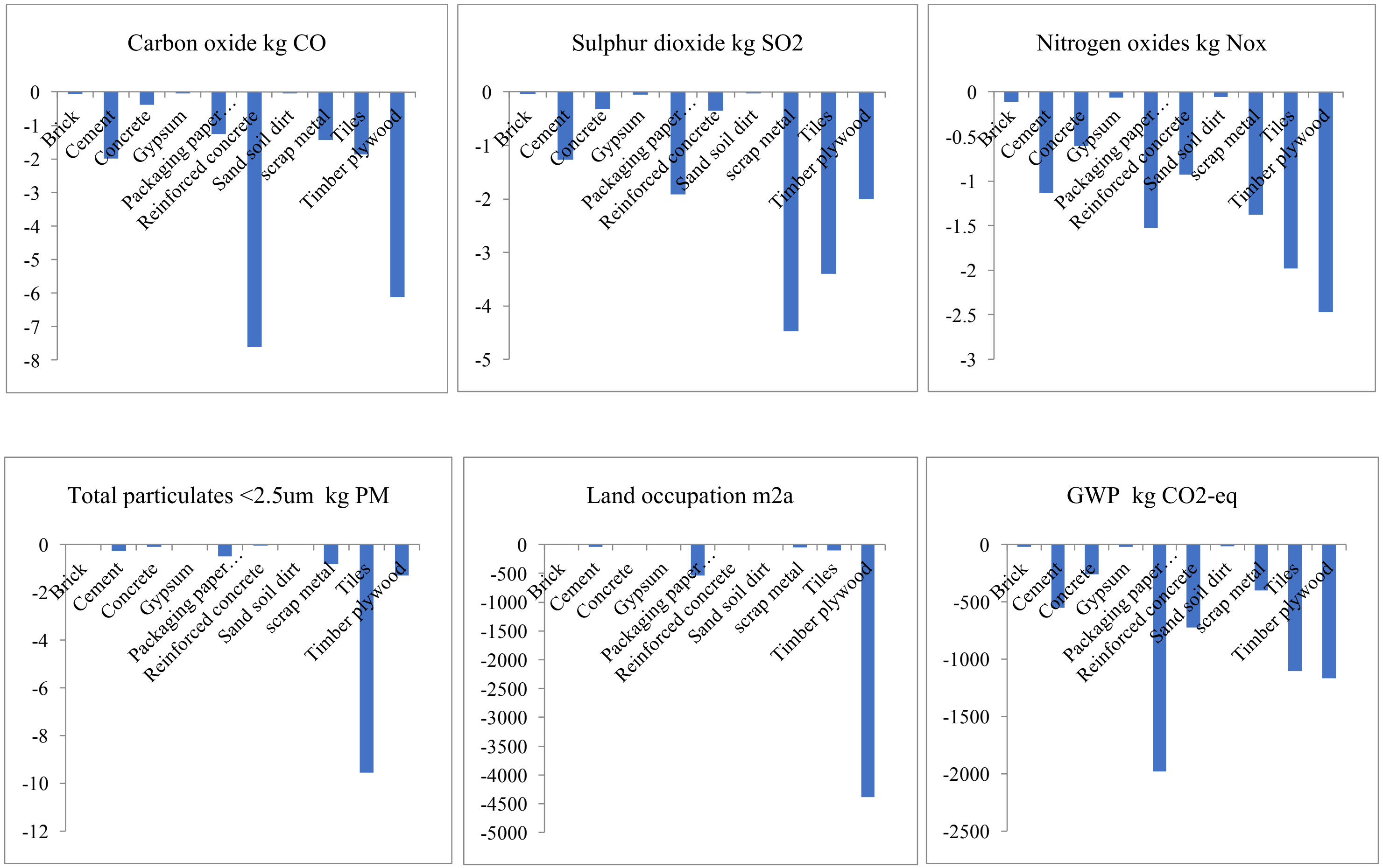

Figure 39: Environmental impacts (CO, SO2, NOx, PM, m2a, kg CO_2 eq) comparison between reducing and landfilling of mixed C&DW.

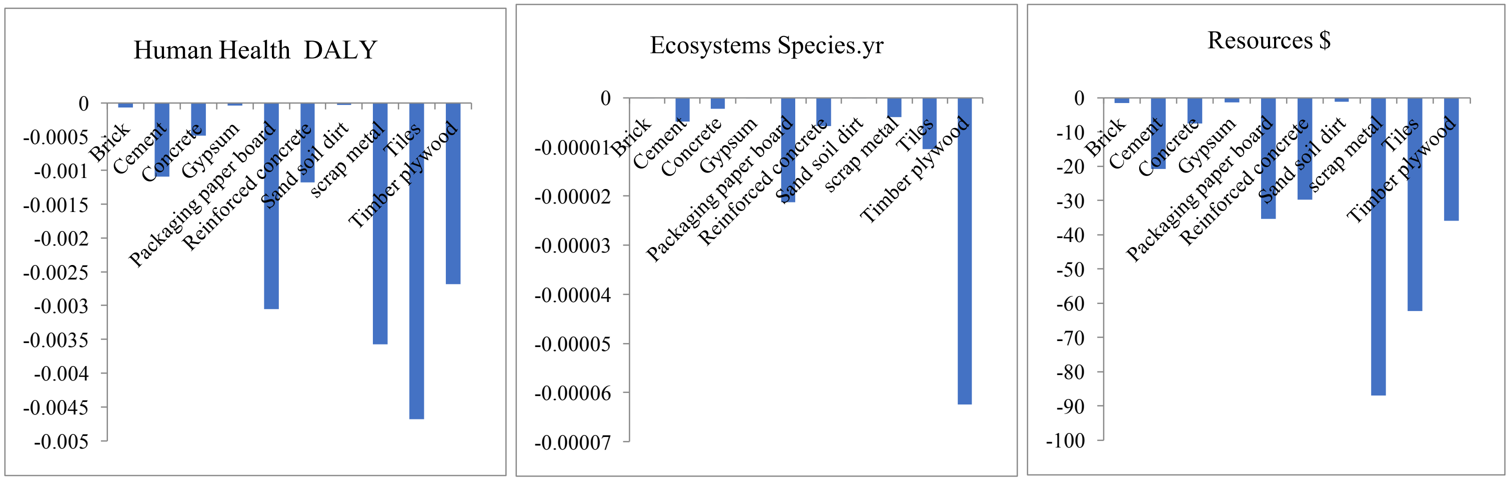

Figure 40: Environmental impacts (CO, SO2, NOx, PM, m2a, kgCO2 eq) comparison between reducing and landfilling of mixed C&DW.

Table 28: Emission savings from recycling 1 t of mixed C&D waste in MRF instead of landfilling

Recycle - Landfill	Carbon oxide kg CO	Sulphur dioxide kg SO_2	Nitrogen oxides kg NO_x	Total particulates <2.5um kg PM	Land occupation m^2a	GWP kg CO_2 eq	Human Health DALY	Ecosystems Species.yr	Resources $
Brick	-0.0393	-0.0161	-0.0561	-0.0048	-1.984	-9.1	-2.09E-05	-4.3E-08	-0.853
Cement	-0.0148	1E-04	0.007	0.0165	-1.18	-0.8	0.0000229	3.08E-08	-0.309
Concrete	-0.0217	-0.0069	0.0018	0.0176	-1.886	-2.9	0.0000152	2.08E-08	-0.502
Gypsum	-0.0226	-0.0062	-0.0262	-0.00145	-1.16	-4.6	-0.00001	-1.65E-08	-0.475
Packaging paper board	-0.0491	-0.1066	-0.0506	-0.0254	-4.01	-1352.5	-0.00163	-8.641E-06	-0.95
Reinforced concrete	-0.0087	1E-04	0.0049	0.0067	-0.7	-1.5	0.0000037	-3.3E-09	-0.21
Sand soil dirt	-0.0056	0.0021	-0.0018	0.0013	-0.2	-1.6	-2.9E-06	-1.95E-08	-0.13
scrap metal	-0.0341	-0.0063	-0.0406	-0.00025	-1.72	-5	-1.08E-05	4.8E-09	-0.647
Tiles	-0.0056	0.0021	-0.0018	0.0013	-0.2	-1.6	-2.9E-06	-1.95E-08	-0.13
Timber plywood	-0.0587	-0.0369	-0.0797	-0.007	-4.11	-615.1	-0.00101	-4.099E-06	-0.86
Total	-0.2602	-0.1746	-0.2431	0.0045	-17.15	-1994.7	-0.002646	-1.279E-05	-5.066

If a process provides negative impacts, it means that after the adoption of the recycling waste management strategy, the avoided impacts are greater than the produced impacts. Negative indicates emissions saving or mitigation, while positive values suggested that the avoided impacts from recycling is lesser than landfilling.

C&DW materials like cement, concrete, reinforced concrete, sand soil dirt, and tiles show positive values in SO_2, NO_x,and total particulates < 2.5 um suggesting that landfilling is a better option to manage these materials in order to reduce the impacts. Packaging, paper, and board and timber plywood show 1325.5 kg CO_2 eq and 615.1 kg CO_2 eq emissions reduction in recycling the waste material. Recycling of packaging, paper, board, and timber plywood shows greatest reduction in overall avoided impacts of human health (DALY), ecosystems (Species.yr), and resources ($) as compared to other C&DW materials. Land occupation of recycling mixed C&DW materials show saving as compared to landfilling (Figure 39 & 40).

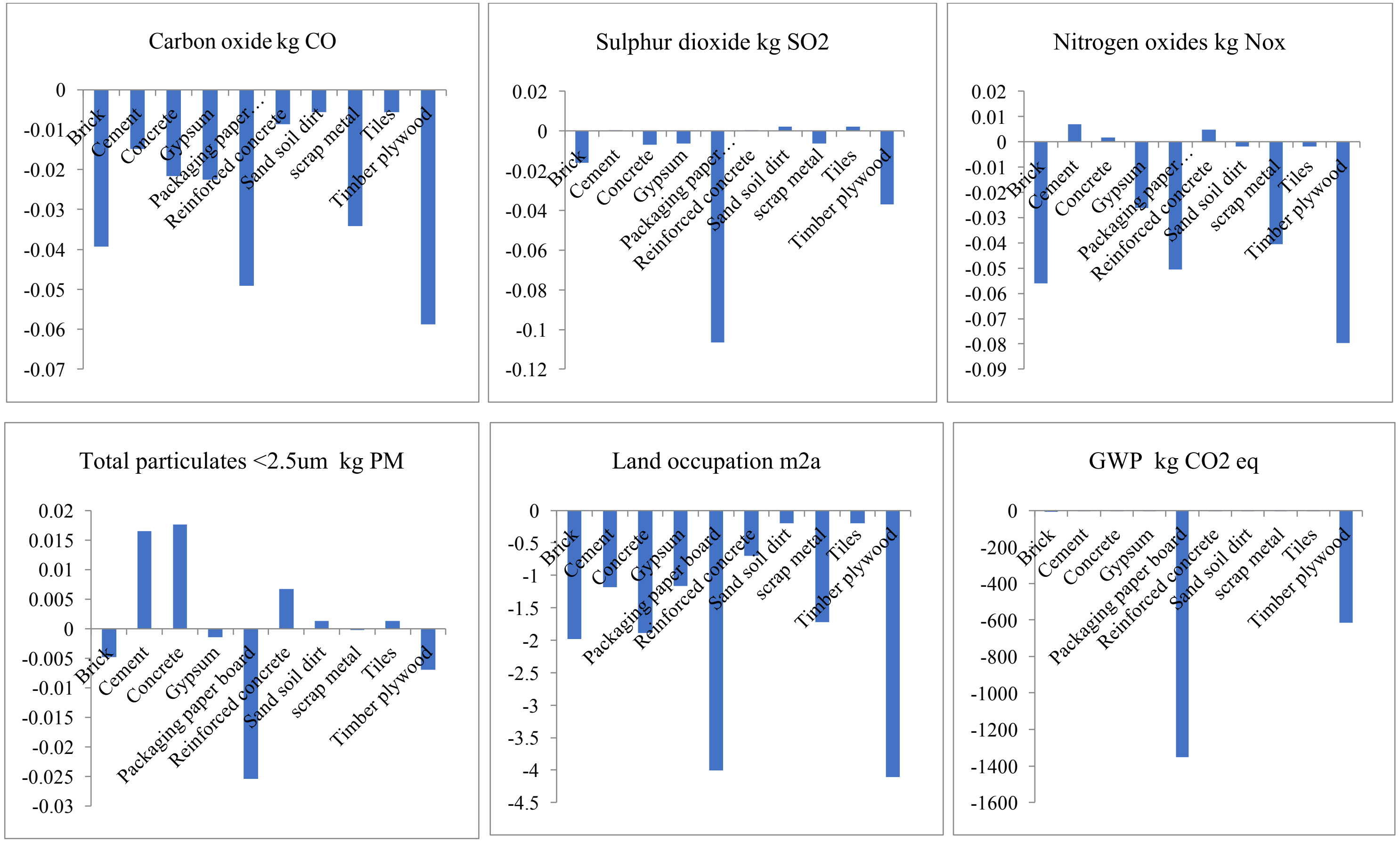

Figure 41: Environmental impacts (CO, SO2, NO_x, PM, m^2a, kg CO_2 eq) comparison between recycling and landfilling of mixed C&DW.

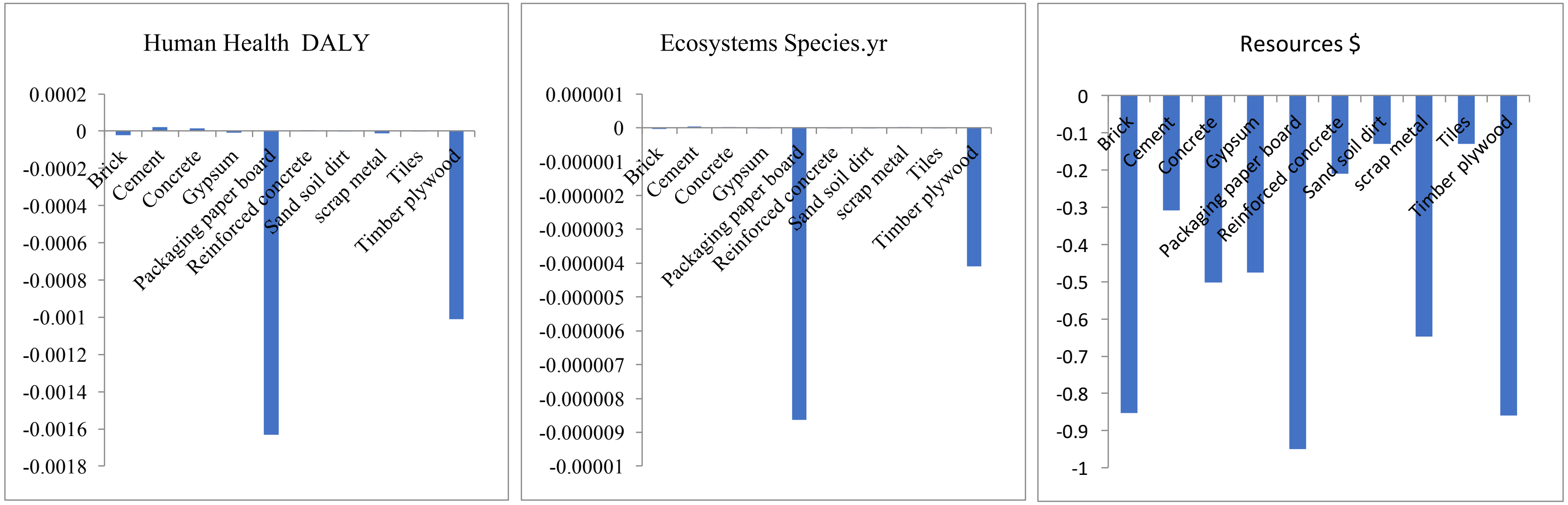

Figure 42: Damage assessment (human health, ecosystems, and resources) comparison between recycling and landfilling of mixed C&DW.

Inert C&DW materials are excluded from incineration scenario and not all of the C&DW materials are suitable for incineration. Packaging, paper, board, scrap metal, and timber plywood waste materials were modelled in incineration waste disposal scenario. Scrap metal rarely go into waste stream as it has high resell value. It yields high value to recycle and reuse it.

Table 29: Emission savings from incinerate 1 t of mixed C&D waste instead of landfilling

Incinerate - Landfill	Carbon oxide	Sulphur dioxide	Nitrogen oxides	Total particulates <2.5um	Land occupation	GWP	Human Health	Ecosystems	Resources
	kg CO	kg SO_2	kg NO_x	kg PM	m^2a	kg CO_2 eq	DALY	Species.yr	$
Packaging paper board	0.0332	-0.075	0.184	-0.0249	-4.59	-1328.7	-0.001504	-8.381E-06	-0.61
scrap metal	0.1083	0.0543	0.2725	0.0114	0.1	511.6	0.0010162	4.4548E-06	0.68
Timber plywood	0.1882	-0.0652	0.255	-0.0166	-5.001	-619.2	-0.0009718	-4.132E-06	-0.93
Total	0.3297	-0.0859	0.7115	-0.0301	-9.491	-1436.3	-0.0014596	-8.058E-06	-0.86

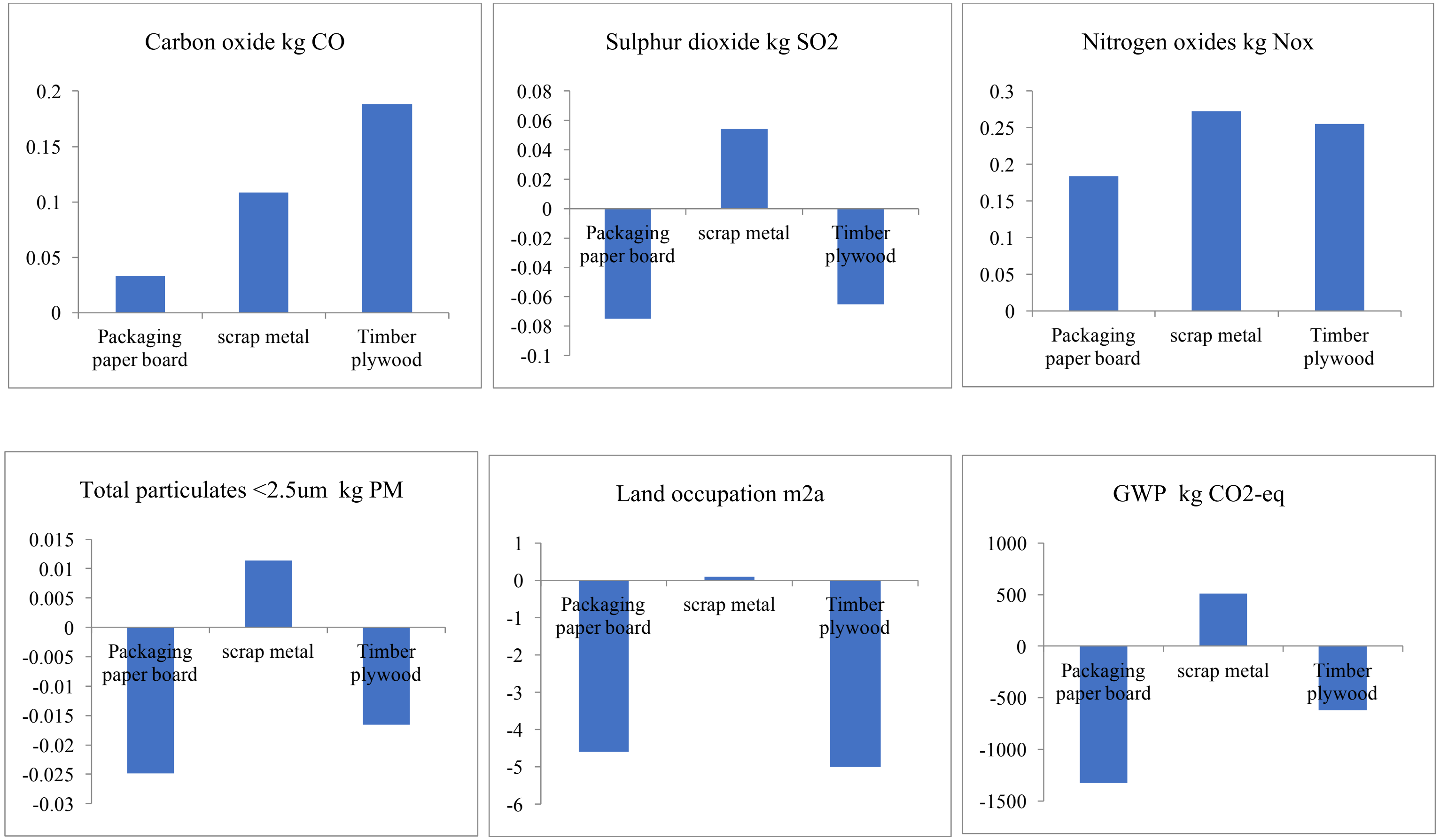

Figure 43: Environmental impacts (CO, SO2, NOx, PM, m2a, kg CO_2 eq) comparison between incineration and landfilling of mixed C&DW.

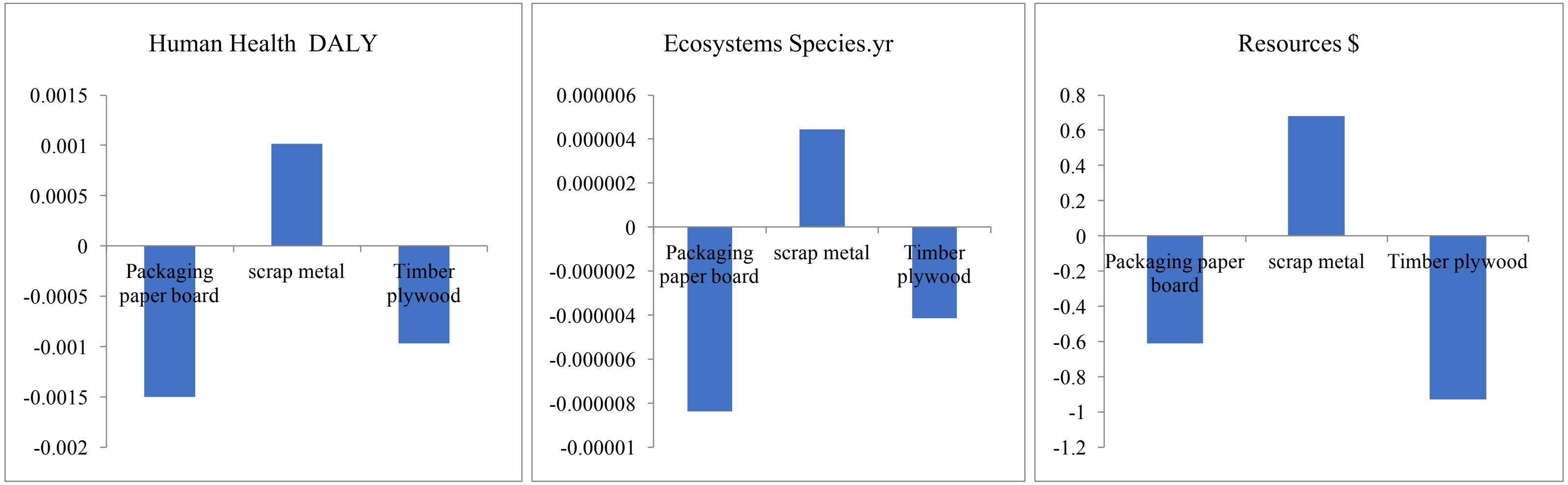

Figure 44: Damage assessment (human health, ecosystems, and resources) comparison between incineration and landfilling of mixed C&DW.

8.4 What-if waste disposal scenarios analyze

Waste disposal scenarios describe the end-of-life route of entire products (mixed C&DW) that may still be reused or disassembled. In disposal scenarios, it contains a number of processes representing the environmental load connected to the scenario, a number of links to waste scenarios that specified to which destinations the product flows. The amounts are expressed as a percentage. The total of all percentages adds up to 100%.

The system boundaries of the scenarios include the transporting of C&DW, material recovery facilities, processing, until the final disposal of all residues. The LCI data from reducing, recycling, incineration, and landfilling of 1 ton of mixed C&DW were used in the what-if waste disposal scenarios analysis.

To evaluate and illustrate the applicability of the carbon impact of C&DW to different waste management routes, 2 types of scenarios were performed.

Scenario 1 - Business as usual in 2016

The scenarios represent the BaU scenario in 2016 and 2025 where all of the C&DW produces from construction site is dump to the landfill. The amount of C&DW reuse on-site is unknown and therefore only the amount of C&DW sent out from the site is considered.

- All of the mixed C&DW material, except scrap metal produce from project site is sent to landfill for final disposal.
- Scrap metal that traditionally yield higher secondary value, is separated from the landfilling waste stream.
- From survey and site observation, food packaging, plastic, construction material packaging, and paper board are usually dump separately as ordinary (municipal solid waste) that are managed and collected by local authority without charges.

Scenario 1 and scenario 2 have the same waste flow; business as usual landfilling all the mixed C&DW generated on-site (Figure 41). The different between S1 and S2 are the total amount of waste generation in 2016 and 2025 (Table 29).

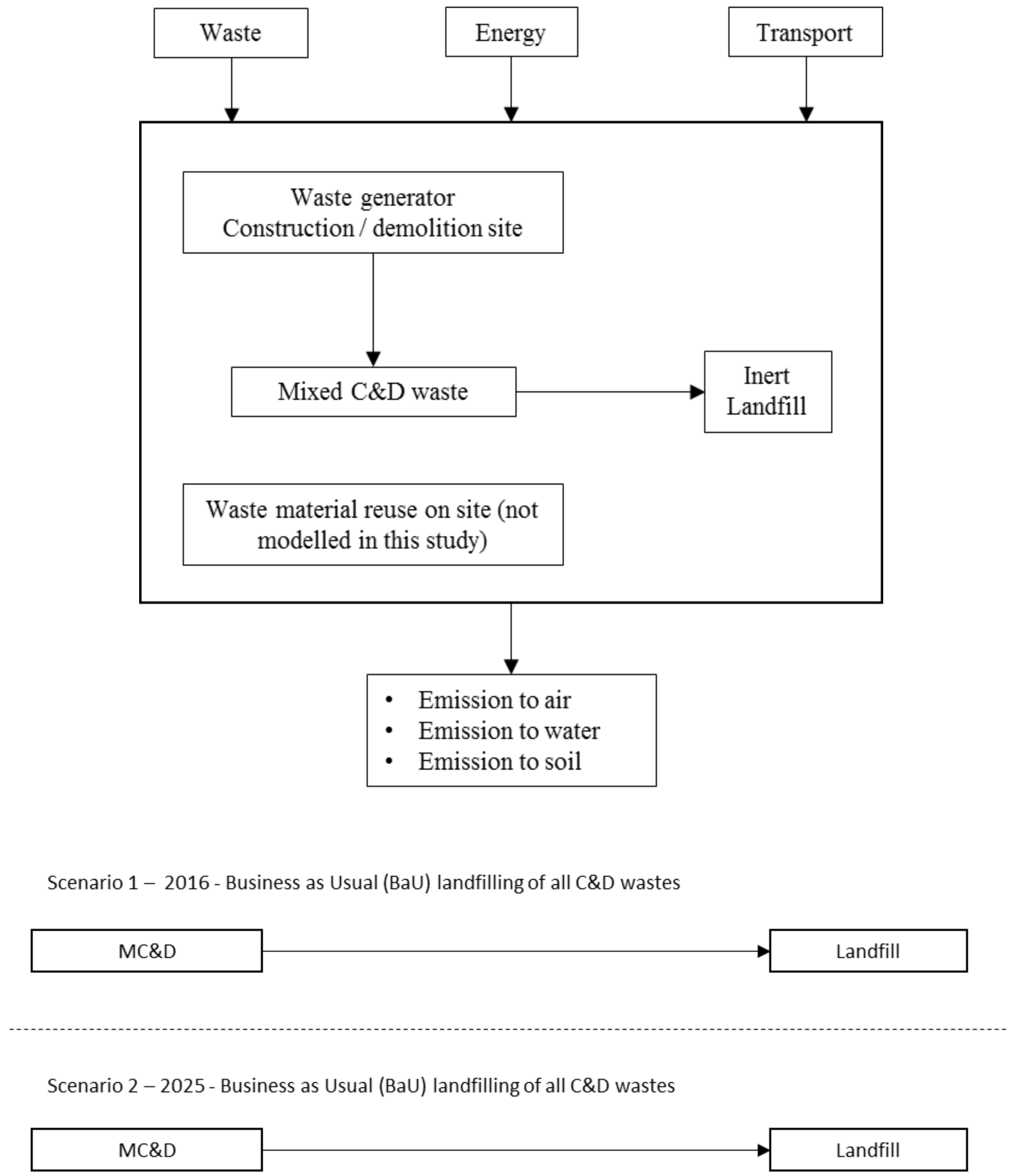

Figure 45: Scenario 1 and 2 - BaU at 2016 and 2025

Table 30: Input data for S1 and S2

Scenario setting		1. BaU 2016	2. BaU 2025
CS - LF	km	61	61
Total waste base year	t	1,847,446	2,339,613
LF machinery compactor	m3	0.794	0.794
Total energy compactor	t.m3	1,466,872	1,857,652
Transport lorry 16-32 t	t.km	112,509,431	142,482,451

**LF machinery compactor refer section 7.3.1*

8.5 Results and Discussion

Table 31: Environmental impacts of 2016 and 2025 business as usual scenarios

Environmental Impacts	Unit	1. BaU 2016	2. BaU 2025
Global Warming Potential 100 years	(kg CO_2 eq)	3.06E+07	3.71E+07
Global Warming Potential 20 years	(kg CO2 eq)	3.26E+07	3.95E+07
Terrestrial acidification	(kg SO2 eq)	60000	71500
Nitrogen oxides	(kg NOx eq)	126000	146000
Particulate matter formation	(kg PM)	21000	25100
Land occupation	(m2a)	4830000	5600000
Photochemical oxidant formation	(kg NMVOC)	35800	42600
Human Health	(DALY)	67.80	81.90
Ecosystems	(Species.yr)	0.18	0.23
Resources	($)	2.48E+06	2.96E+06
Human Health	(MPt)	1.99	2.40
Ecosystems	(MPt)	0.0794	0.1010
Resources	(MPt)	2.03	2.41

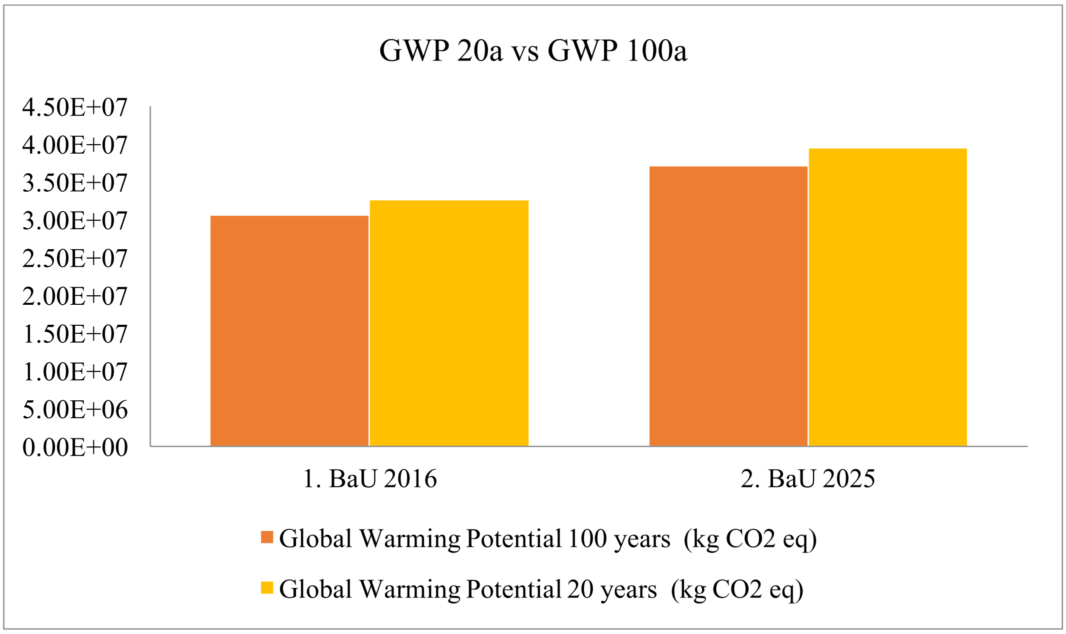

Figure 46: BaU 2016 and 2025 scenarios - Global warming potential 20 year vs 100 year

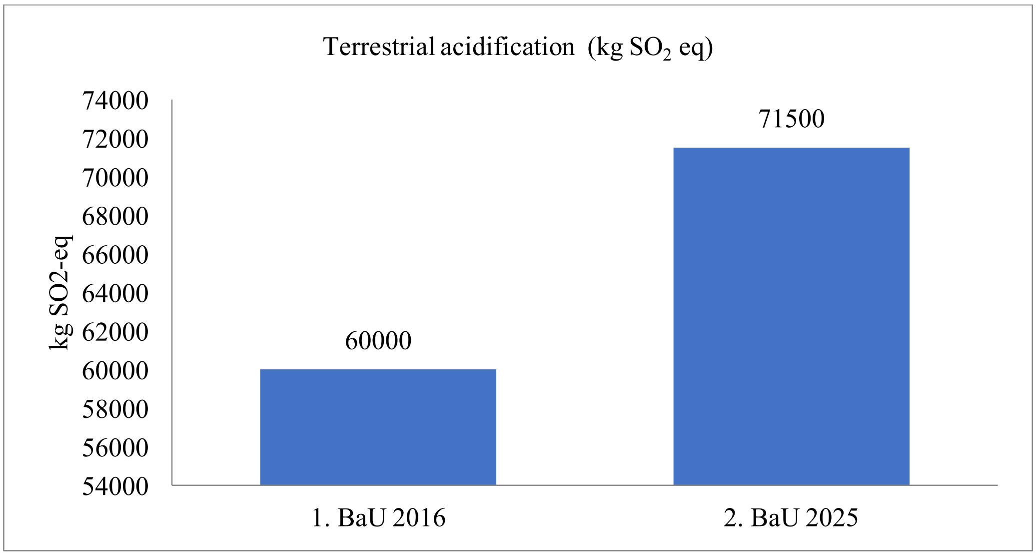

Figure 47: BaU 2016 and 2025 scenarios - Terrestrial acidification

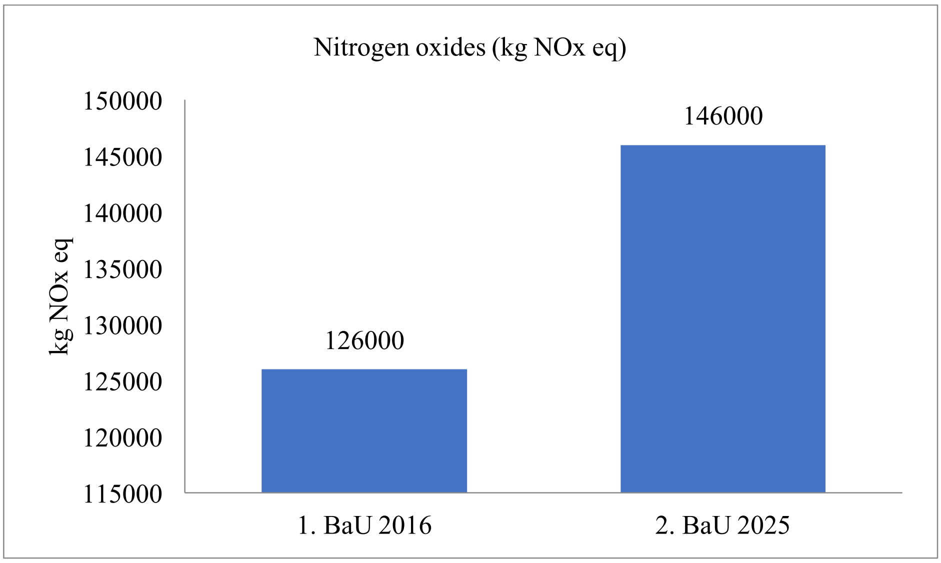

Figure 48: BaU 2016 and 2025 scenarios - Nitrogen oxides

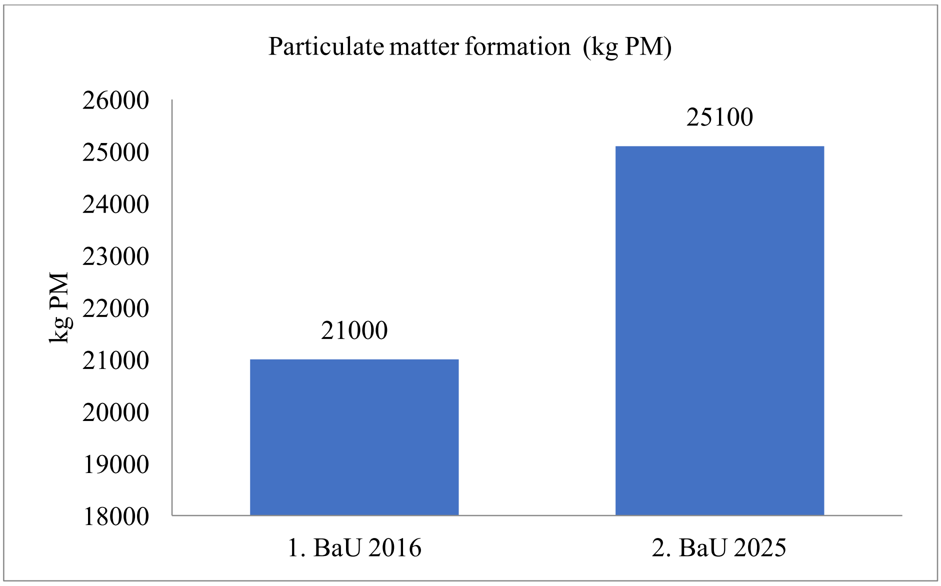

Figure 49: BaU 2016 and 2025 scenarios - Particulate matter formation

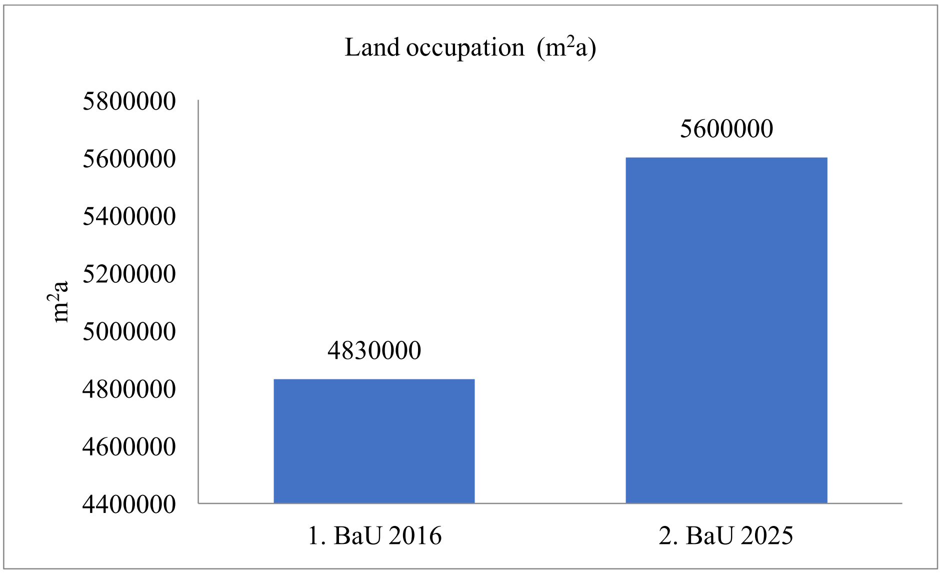

Figure 50: BaU 2016 and 2025 scenarios - Land occupation

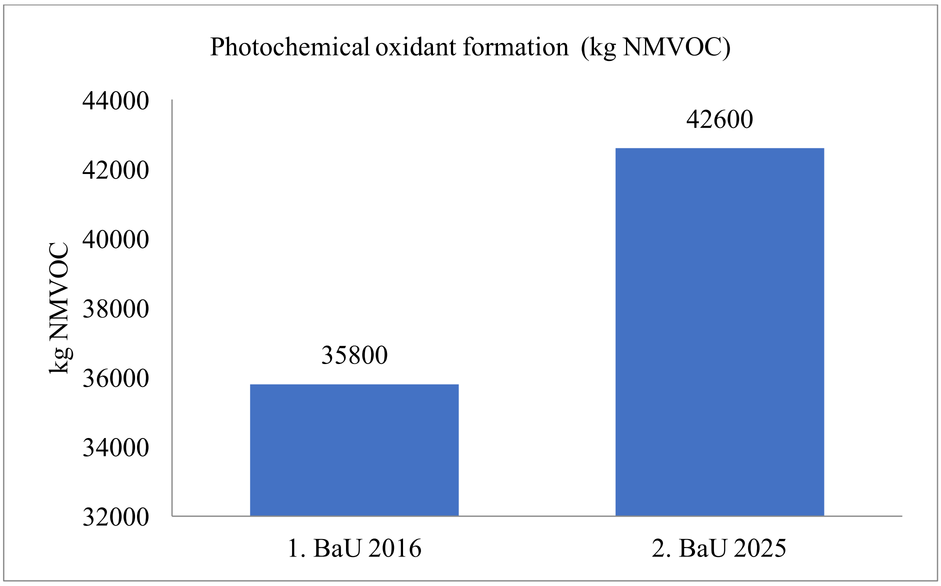

Figure 51: BaU 2016 and 2025 scenarios - Photochemical oxidant formation

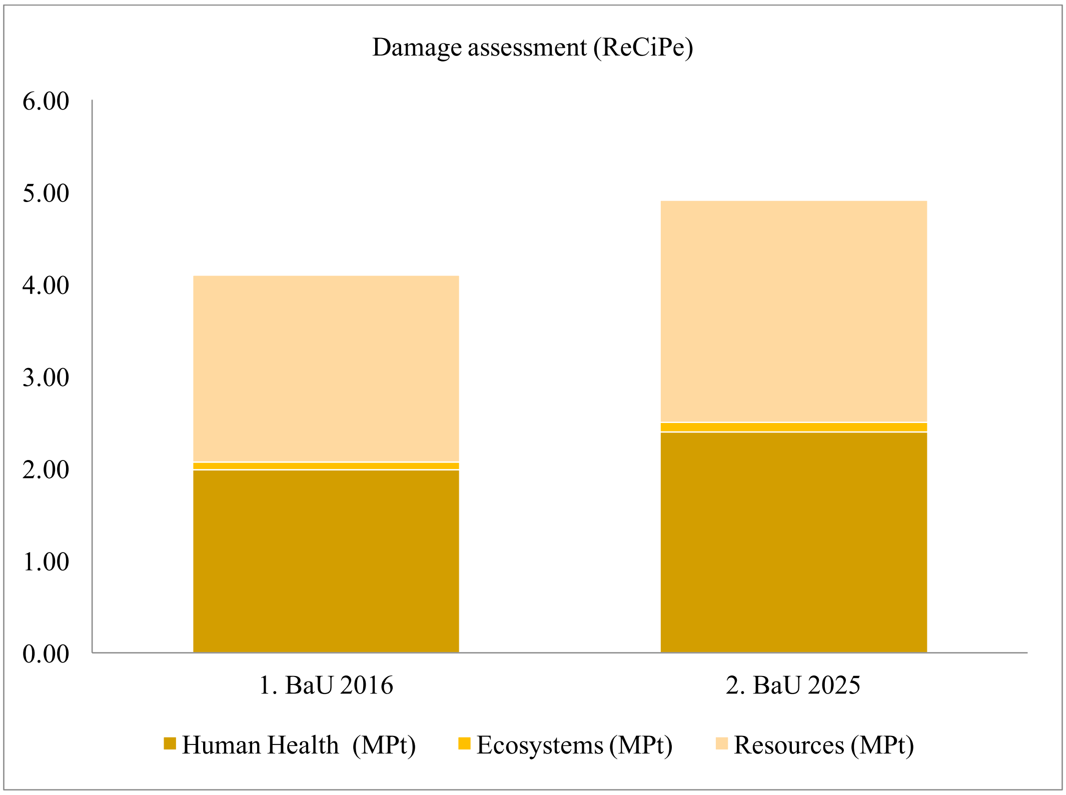

Figure 52: Comparison of damage assessment of scenario 1 and scenario 2 (Endpoint H, World ReCiPe H/A, Single score)

The damage assessment (Figure 55) shows that the damage assessment of S1- BaU will continue to rise by approximately 20% at year 2025, without any counter-measure.

The future of C&DW management is affected by many different variables such as policies development, construction technologies, waste generation and composition, and recycled materials acceptance rate. If the BaU practices continue to 2025, the environmental damages are estimated to increase around 20% (Figure 50). The what-if scenarios presented in the next section illustrated the uncertainties in the future of C&DW management.

Environmental performance of C&DW disposal scenario can be improved with better construction method, for instant, a shift from conventional construction method to IBS construction method to reduce the waste generation on-site. Diversion of C&DW from entering landfill waste stream could possibly change the environmental performance too. In concrete waste LCA (chapter 5), emission from transportation is identified as one of the main attribute in influencing the feasibility of a waste management option. Hence, three of the attributes were evaluated in the what-if scenarios:

i) maximum diversion of C&DW away from landfill into MRF for recycling,
ii) a mobile MRF is built at a minimal distance away from the center of C&DW generation source, an
iii) shift from conventional construction method to IBS construction method to reduce waste generation on-site.

There are 6 what-if scenarios (Scenario 3 – 8) depicted in Figure 53. The combinations of different attributes in influencing the environmental performance profile are depicted in Table 32.

Scenarios 3 - 8 were designed as the counter-measure scenario to the BaU scenarios (S1 and S2). Scenario 3 described the mixed C&DW materials are separated into 2 categories: recyclable and non-recyclable before transporting it out from site. Recyclable C&DW materials are sent to material recovery facilities (MRF) for separation and recycling. Non-recyclable C&DW materials are sent to landfill.

Scenario 4 depicted the maximum diversion of C&DW diversion from landfill into recycling stream.

Scenario 5 described the maximum diversion of C&DW into recycling stream and the distance between CS to MRF is assumed to be at minimum, 3 km.

Scenario 6 focused on shifting of construction method from the conventional construction method to IBS method, to reduce waste generation. The waste management is maintained at BaU, landfilling. Total waste generation for IBS method is estimated at 367,045 tons (from chapter 4).

Scenario 7 described the combination of IBS method in minimizing waste generation and maximum diversion of C&DW materials into MRF for recycling.

Scenario 8 described the combination of scenario 7 with minimal distance to MRF. In this scenario, MRF is assumed to be located at a minimal distance of 3 km away from CS. Refer table 32 and figure 53 for details input data analysis.

Table 32: What-if scenarios base input data

Scenario setting		S3. Bau 50 % div 2025	S4. MaxDiv 2025	S5. MaxDiv MinDist 2025	S6. BaU IBS 2025	S7. IBS MaxDiv 2025	S8. IBS maxdiv mindist 2025
CS - LF	km	61			61		
CS - MRF	km	36.1	36.1		36.1	36.1	
CS - MRF MinDis	km			3			3
Total waste base year	t	2,339,613	2,339,613	2,339,613	367,045	367,045	367,045
LF machinery compactor	m3	0.794			0.794		
MRF machinery energy	kWh /t	3.11	3.11	3.11		3.11	3.11
Total energy compactor	t.m3	928,826			298,407		
MRF machinery energy	kWh	3,633,712	7,267,424	7,267,424		1,140,132	1,140,132
Transport lorry 16-32 t	t.km	113,471,246	84,460,041	7,018,840	22,353,016	13,250,310	1,101,134

The life cycle inventories data input were obtained from Chapter 5 (concrete waste) LCI and MRF LCI refer to section 7.3.2

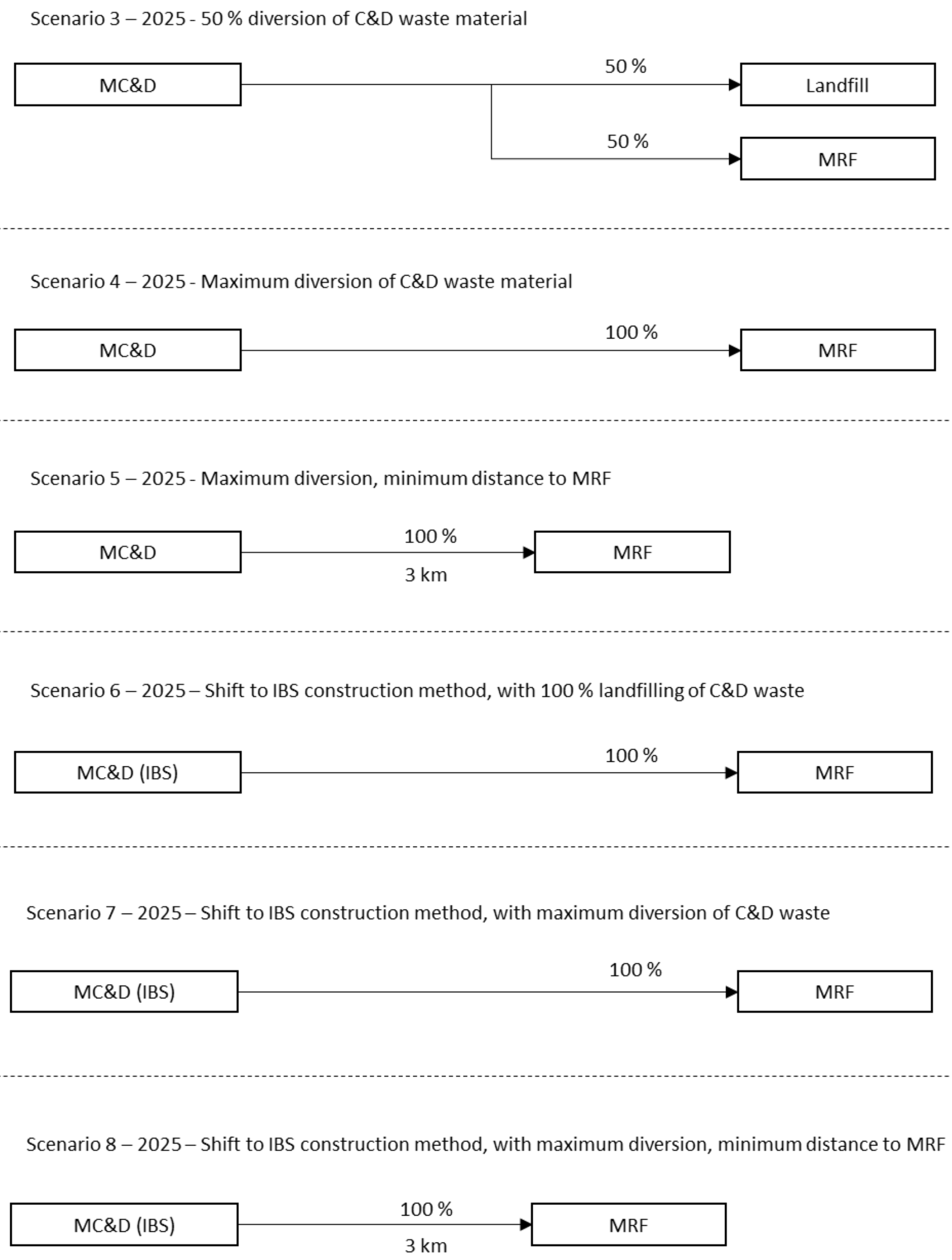

Figure 53: What-if scenarios analysis diagram

8.6 What-if scenarios analysis and discussion

Table 33: Environmental performances of what-if analysis scenarios

Environmental Impacts	Unit	3. Bau 50 % div 2025	4. MaxDiv 2025	5. MaxDiv MinDist 2025	6. BaU IBS 2025	7. IBS MaxDiv 2025	8. IBS maxdiv mindist 2025
GWP 100 years	(kg CO_2 eq)	2.32E+07	1.95E+07	6.75E+06	7.18E+06	3.10E+06	1.10E+06
GWP 20 years	(kg CO_2 eq)	2.45E+07	2.07E+07	7.32E+06	7.71E+06	3.31E+06	1.20E+06
Terrestrial acidification	(kg SO_2 eq)	41200	39200	20100	15100	6200	3220
Nitrogen oxides	(kg NO_x eq)	48500	29900	12300	34100	4460	1700
Particulate matter formation	(kg PM)	15300	15000	8350	5200	2400	1350
Land occupation	(m^2a)	1890000	1210000	337000	1350000	143000	5390
Photochemical oxidant formation	(kg NMVOC)	18600	12300	1870	8970	2010	377
Human Health	(DALY)	49.40	41.50	14.70	16.40	6.62	2.43
Ecosystems	(Species.yr)	0.21	0.18	0.06	0.03	0.03	0.01
Resources	($)	1.46E+06	1.12E+06	3.31E+05	6.26E+05	1.78E+05	5.40E+04
Human Health	(MPt)	1.45	1.22	0.43	0.47	0.19	0.07
Ecosystems	(MPt)	0.0912	0.0797	0.0240	0.0149	0.0127	0.0039
Resources	(MPt)	1.19	0.91	0.27	0.51	0.15	0.04

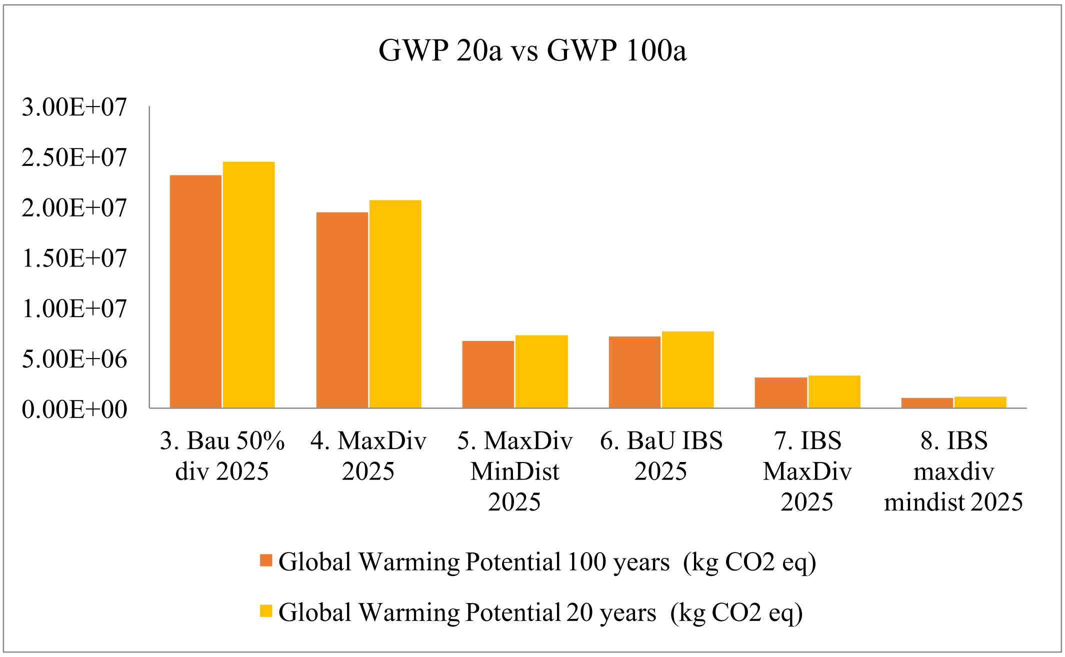

Figure 54: S3 –S8, global warming potential 20 year vs 100 year

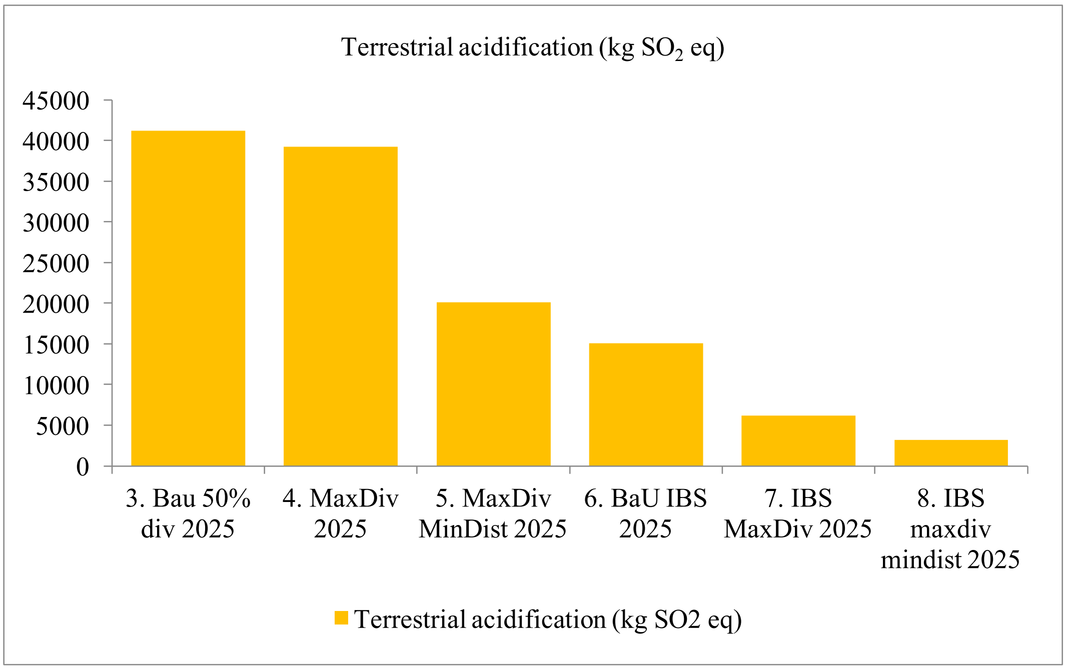

Figure 55: S3 –S8, terrestrial acidification impact

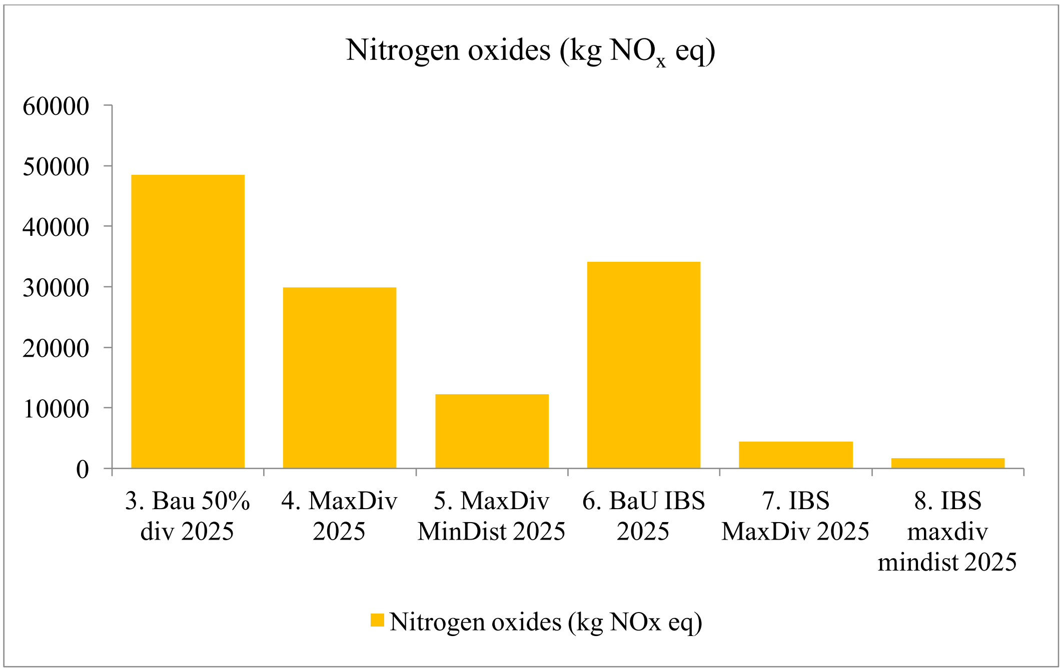

Figure 56: S3 –S8, Nitrogen oxides

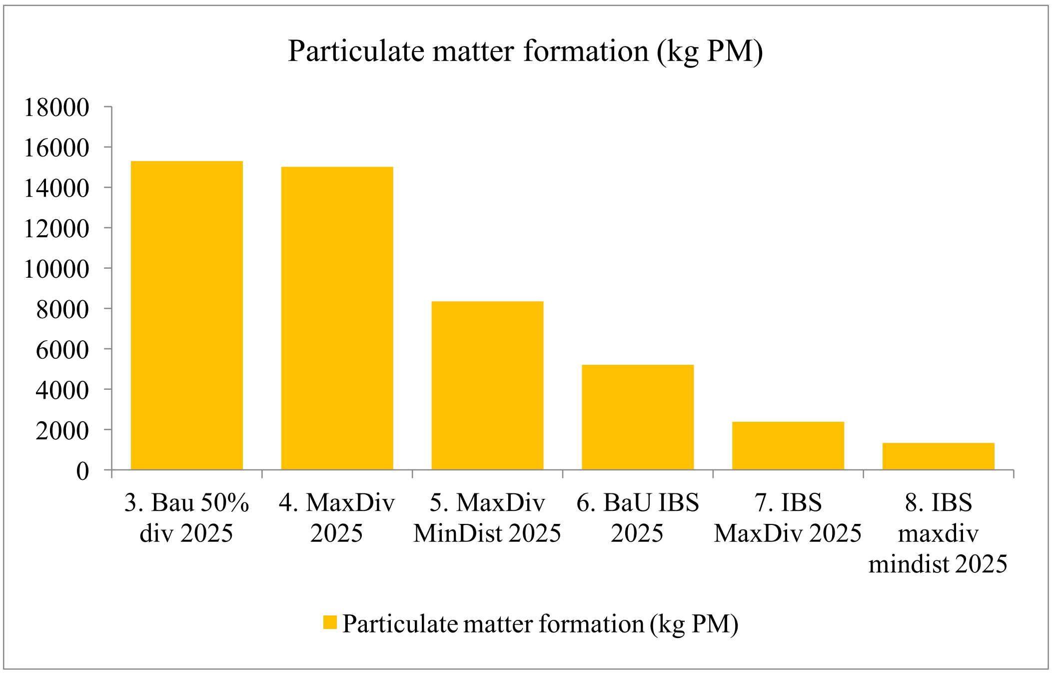

Figure 57: S3 –S8, particulate matter formation

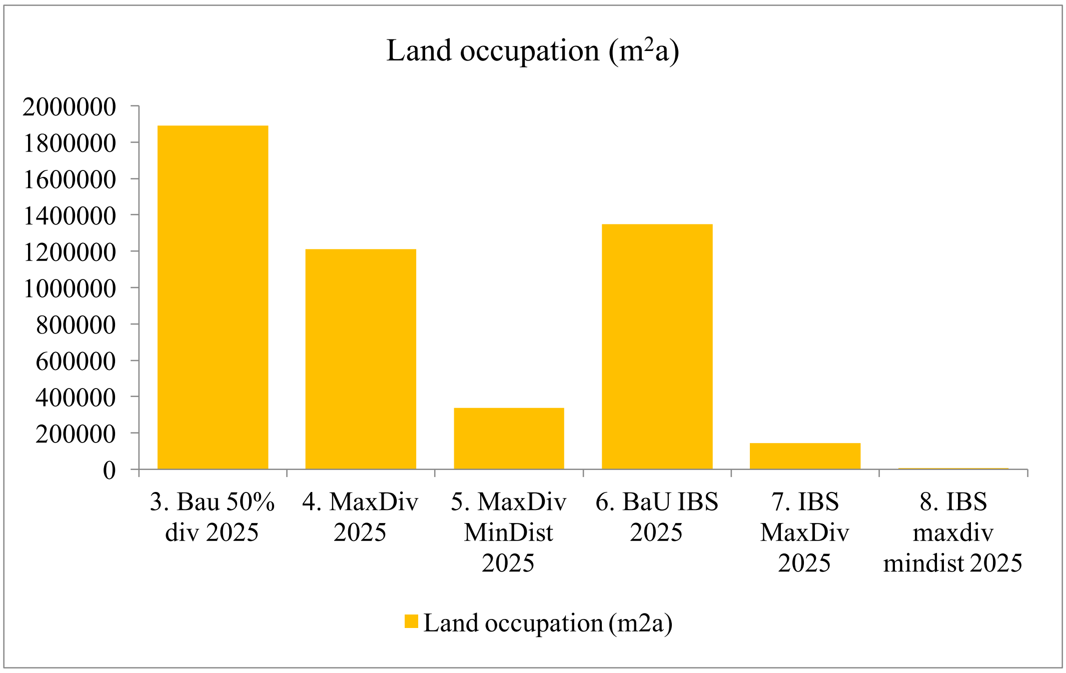

Figure 58: S3 –S8, Land occupation

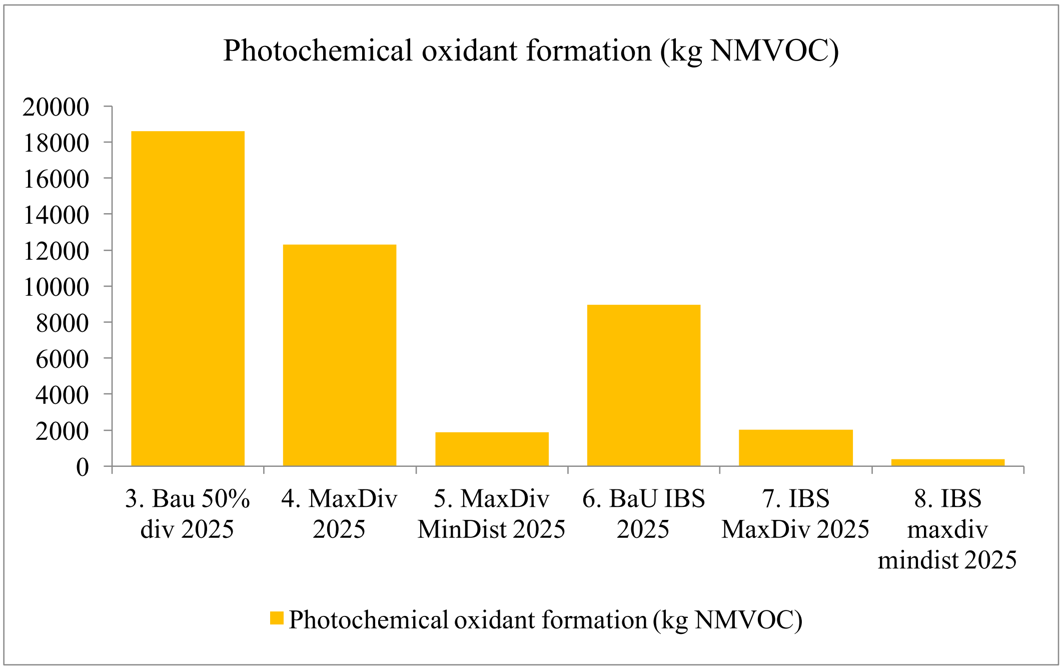

Figure 59: S3 –S8, Photochemical oxidant formation (kg NMVOC)

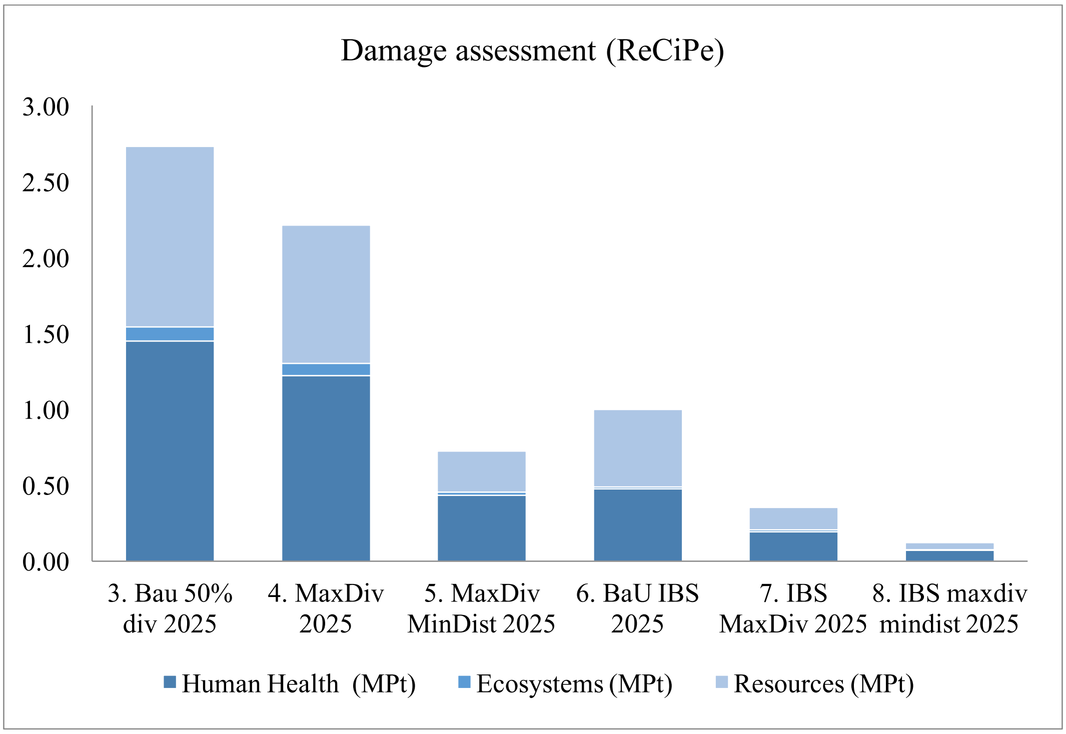

Figure 60: S3 –S8, Damage assessment

8.7 Summary of key findings and Conclusions

Construction and demolition waste is estimated to increase 21.2 % (BaU 2016 vs BaU 2025) by 2025 should the business as usual (BaU) landfilling is maintained.

In order to reduce the total waste generation and environmental damages caused by landfilling of C&DW, maximum diversion of C&DW to recycling could reduce 24.2 % of carbon emission and 61 % of saving in land occupation.

With maximum diversion and minimum distance to MRF, it could reduce 51.2 % of carbon emission and 75% of saving in land occupation.

Reducing the total waste generation with shifting of construction method to industrialized building system (IBS) could further enhance the saving of carbon emission and land occupation. This scenario is depicted in Scenario 8.

The negative impacts derived from landfilling activity could be significantly reduced through shifting of current construction method to IBS construction method, reusing, recycling, and lastly reducing the travel distances between construction sites to material recovery facility (MRF). This optimal scenario is presented in waste disposal Scenario 8. Lowest environmental damages or the most environmental friendly scenario could reduce overall 96 % of carbon emission in 2025 and saving of 99.9 % of land occupation (scenario 1 vs scenario 8).

What-if scenarios show a relatively similar trend in different environmental impacts suggesting that shifting to IBS construction method to reduce waste generation would reduce overall environmental and cost impacts, reduce travel distance to MRF would increase recycling feasibility, and maximal recycling would further increase the avoided burden in producing new raw materials.

9 Conclusions

The construction industry has continued to expand with the global economy as a driving force in the transformational growth into developed economies; the industry has now become a significant major solid waste contributor. Construction and demolition waste (C&DW) continues to increase in parallel with economic growth in emerging and developing countries like Malaysia and the improper management of C&DW often lead to considerable environmental damages. It raised the questions of how to achieve sustainability to reduce its environmental impacts and to contribute to GHG emissions mitigation. This research developed goals aligned to achieving sustainability through building the waste generation data, investigating the potential environmental impact, and to forecast the future 2025 waste management based on theoretical methodologies.

The theoretical method presented in chapter **3** to demonstrates a less burdensome framework for waste generation rate (WGR) estimation through available secondary data input, interviews with site personnel, and periodic site observation. Such method is significantly more practicable than the costly on-site hand sorting or machinery-sorting method. The findings from this study also demonstrate the role of the construction method in influencing WGR, highlighting the benefits of transitioning from the conventional construction method (CCM) to the mixed-construction method (MCM), particularly in respect to reducing WGR on-site. WGR data obtained through this method may be applied to a broader series of case studies, and may serve as the foundation for a regional C&DW database and C&DW projections. With pending massive increases in Malaysian housing demand, and the revival of previously abandoned projects, the opportunity for utilizing such regional WGR data is clear, especially where such data suggests the potential for future growth in the C&DW recycling industry. Where there are available recycling facilities, the economics may shift to justify an increase in recycling C&DW.

The point source waste assessment data method used in **chapter 4** to estimate and to extrapolate the amount of total waste generation in 2016 and 2025 produced nationally, is known to be a basic and general method. In Malaysia, there is no known record of C&DW generated, thus employing this method is a simplification and it is expected to be the trend setter towards better characterization and recording of C&DW generated, nationally. Accurate record of the precise amount of C&DW generated, if any, could easily modified the accuracy of the estimation accordingly. Since the method used in this method makes use of readily available statistic data (total area built, construction cost, inflation rate, economy growth), the methodology used is well suited for periodic update when newer statistic data made available. According to Franklin Associates (1998b), waste assessment should change slowly over the time as the industry is known for it slow pace in adopting to changes. Composition of waste from building demolition should change even slower than waste from construction project. Lack of basic data from other projects (infrastructure, industrial, commercial building) such as waste generation, composition, and recovery rate might hinder the waste management system planning.

One of the main intention of life cycle assessment (LCA) is to assist the stakeholders in making environmental sound science, data-based decision making. LCA offers interpretation of comprehensive data and results into a series of quantitative measures easing decision makers to move forward toward developing a sustainable waste management. C&DW materials were evaluated with different system boundaries highlighting the alternatives in waste management. The system boundaries and waste scenarios address the consequences of possible decisions, parameters, and alternatives. The LCA study is divided into three chapters that offered interesting outcomes to better manage C&DW:

- Wood waste LCA, demonstrating the incineration with energy recovery would likely offset the environmental impact caused by waste landfilling;
- Concrete waste LCA and LCC, demonstrating the combination of environmental and economic indicator in influencing the decision making process in waste management; and
- Mixed C&D waste LCA, demonstrating the waste disposal scenario as the end-of-life and identify the optimal solution to manage the mixture of C&DW.

In order to align decision making with the most environmental sound waste management scenario, a holistic waste management scenario must allow the decision maker to overcome its transaction costs or at least minimize its losses. In chapter 7 (life cycle environmental and economic assessment of concrete waste), the integration of economic and environmental parameters is explicitly important in influencing stakeholders to pursue recycling instead of landfilling. It illustrated the importance of integrating economic and environmental concerns in making environmentally sound decisions and cost-effective sustainable waste management decision. This study also analyzed the industry's actual decision-making regarding C&DW management costs and practices. Recycling of C&DW will happen when its eco-efficiency indicators show lower environmental cost ratio or when the direct economic benefits outweigh landfilling, regardless of costs to externalize to the environment.

Mixed C&DW is assessed within a study boundary that reflects the actual industry practice of disposing waste without separation. The purpose of this study is to investigate the consequences of specific discrete assumptions and parameters in influencing the existing landfilling system. Eight what-if scenarios were built to illustrate a number of plausible parameters and routes that pose challenges for waste recycling business. The scenarios were built based on three parameters: i) maximum (100%) diversion of waste into recycling stream, ii) reduce travel distances and placement of material recovery facility (MRF) within three kilometers from construction site, and iii) waste reduction through shifting of construction method to industrial building system (IBS). The total GHG emissions caused by C&DW is estimated to increase 21.2 % from 2016 to 2025 if current business as usual (landfilling) practice continues. GHG emissions will increase along with total amount of waste generation in 2025. Maximum diversion of C&D waste to recycling instead of landfilling could reduce 24.2% of GHG emissions and reduce 61 % of land occupation. Reducing travel distances between waste source and destinations could further reduce 51.2 % of GHG emissions and increase savings in land occupation by 75%. A shift of construction method from conventional construction method to industrial building system (IBS) could potentially reduce the amount of C&D waste generated and eventually reduce the GHG emissions to 96 % and reduce 99 % of associated land occupation. The sensitivity study shows that the outputs are sensitive to the savings made in the three parameters.

Findings from chapter 6, 7, and 8 suggested that landfilling of CD&W is proven environmentally unsustainable method. But it will continue until economic incentives are demonstrated to favor recycling for construction firms. It is rare that a decision must be made solely in favor of either internal firm cost interests or external environmental and social interests; rather it is generally a question of understanding and optimizing both considerations toward holistic efficiency and sustainability. Intervening forces, such as government and regulatory policy and enforcement, may modify the economic incentives, and thus the stakeholders' decision making process to promote recycling over landfilling. Recycling tax incentives to a company that recycles is the most common stimulant to shift the decision making paradigm from landfilling to the recycling. Policy makers could also impose coercive policies such as waste tax penalization to shift economic costs directly to those rendering the environmental impacts. It is useful for researchers, industry decision makers, and also environmental economists to incorporate such cost impacts when recommending sustainable waste management policies.

This current research raises many interesting questions for further exploration, specific to C&DW management and recycling in Malaysia, including:

- Having quantified waste generation by construction method, what options are feasible to promote adoption of optimal practices?
- What practices will most effectively increase data collection of certain indicators measuring sustainability?
- What steps can be taken to promote public and private industry engagement in Malaysian sustainable development?
- The impact and possibilities of the "Fourth Industrial Revolution" in C&DW management, to promote a circular economy and increase awareness.
- The responsiveness and dynamism of the waste management industry and recycling culture in building a sustainable and recycling nation.
- How the waste management industry's resilience to change may be overcome by organic introduction of certain innovative technologies and practices?
- Which ways, and to what extent, the "Internet of Things" could change the world of waste management and how could it facilitate in promoting and influencing a sustainable living lifestyle?
- What additional sustainable solutions or information could be gathered through technology and social media platform to organically form a recycling community?

A complete C&DW management system should proactively gather, store, and analyze large data sets including waste type, waste generation rate, waste flow, and other environmental impact data is vital in supporting the decision making. A quantitative database is crucial in assisting stakeholders in making data-driven and sound-science decisions to achieve sustainability. Global GHG emission growth may seem inexorable, but mitigation through choosing a sustainable waste management solution could help developing countries like Malaysia in decoupling economic growth from GHG emissions growth. Future studies should also consider the waste management tapping into the internet of things (IoT). Big data practices would bridge C&DW management into unlimited opportunities to optimize recycling, improve transportation route, increase efficiency, and to reduce environmental impact and cost.

References

Balasbaneh, A. T., & Marsono, A. K. B. (2012). Environmental Life-Cycle Assessment of a Single-Family House in Malaysia: Assessing Two Alternative IBS Frames. *International Journal of Emerging Technology and Advanced Engineering, 2*(11), 534 - 540.

Begum, R. A., Siwar, C., Pereira, J. J., & Jaafar, A. H. (2007). Implementation of waste management and minimisation in the construction industry of Malaysia. *Resources, Conservation and Recycling, 51*(1), 190-202.

Begum, R. A., Siwar, C., Pereira, J. J., & Jaafar, A. H. (2009). Attitude and behavioral factors in waste management in the construction industry of Malaysia. *Resources, Conservation and Recycling, 53*(6), 321-328.

Bina, J. U. (2017). Construction cost handbook Malaysia 2016 & 2017. from Malaysia: www.langdonseah.com (accessed Feb 12, 2017)

BIS. (2010). Estimating the amount of CO2 emissions that the construction industry can influence. from Department for Business Innovation & Skills: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/31737/10-1316-estimating-co2-emissions-supporting-low-carbon-igt-report.pdf (accessed November 7, 2015)

Biswas, W. K. (2014). Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia. *The International Journal of Life Cycle Assessment, 19*(4), 732-744.

Bovea, M. D., & Powell, J. C. (2016). Developments in life cycle assessment applied to evaluate the environmental performance of construction and demolition wastes. *Waste Management, 50*, 151-172.

Burton, E., & Friedrich, N. (2008). Net waste tool - guide to reference data. from http://nwtool.wrap.org.uk/Documents/WRAP%20NW%20Tool%20Data%20Report.pdf (accessed December 3, 2015)

Butera, S., Christensen, T. H., & Astrup, T. F. (2015). Life cycle assessment of construction and demolition waste management. *Waste Management, 44*, 196-205.

Carlsson Reich, M. (2005). Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). *Journal of Cleaner Production, 13*(3), 253-263.

Cement Association of Canada, C. (2016). *Concrete Design Handbook – 4th Edition* (4th ed.). Toronto, Canada.

Chowdhury, R., Apul, D., & Fry, T. (2010). A life cycle based environmental impacts assessment of construction materials used in road construction. *Resources, Conservation and Recycling, 54*(4), 250-255.

Consonni, S., Giugliano, M., & Grosso, M. (2005). Alternative strategies for energy recovery from municipal solid waste. *Waste Management, 25*(2), 137-148.

Department of Statistic, M. (2012-2015). Quarterly construction statistics. Department of Statistics Malaysia Retrieved from https://newss.statistics.gov.my/newss-portalx/ep/epProductFreeDownloadSearch.seam (accessed December 20, 2015)

Department of Statistic, M. (2015). Quarterly construction statistics 2015 Quarter 1. Department of Statistics Malaysia Retrieved from https://newss.statistics.gov.my/newss-portalx/ep/epProductFreeDownloadSearch.seam (accessed December 20, 2015)

Department of Statistic, M. (2016). Economic cencus 2016 - Mining and quarrying. Department of Statistics Malaysia Retrieved from https://www.dosm.gov.my/v1/index.php?r=column/cthemeByCat&cat=97&bul_id=dVE3UXhFcVkzTFVPVXVWNkt6NDlpUT09&menu_id=TXdvYTlvQXVlTFhVOUJ6NVVESVBNUT09 (accessed July 20, 2017)

Ding, T., Xiao, J., & Tam, V. W. Y. (2016). A closed-loop life cycle assessment of recycled aggregate concrete utilization in China. *Waste Management*.

Duan, H., & Li, J. (2016). Construction and demolition waste management: China's lessons. *Waste Management & Research, 34*(5), 397-398.

EU, E. U. (2011). Supporting Environmentally Sound Decisions for Construction and Demolition (C&D) Waste Management. from Italy: http://eplca.jrc.ec.europa.eu/uploads/waste-Guide-to-LCTLCA-for-C-D-waste-management-Final-ONLINE.pdf (accessed July 28, 2017)

Eurostat (2015) Waste Statistics. From European Union, Publications (Sept 2015):http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics (accessed 7 Dec 2015)

Eusuf, M. A., Ibrahim, M., & Islam, R. (2012). The construction and demolition wastes in Klang Valley, Malaysia. *Journal of the Malaysian Institude of Planners, X*(2012), 99-124.

Fatta, D., Papadopoulos, A., Avramikos, E., et al. (2003). Generation and management of construction and demolition waste in Greece—an existing challenge. *Resources, Conservation and Recycling, 40*(1), 81-91.

Fauziah, S. H., & Agamuthu, P. (2003). Municipal solid waste management: a comparative study on selected landfill in Selangor. *Proceedings of Environment 2003 Environmental Management and Sustainable Development for Better Future Growth.*, Penang, Malaysia. February 18 – 19, 2003 pp 434- 437, USM Publisher

Foo, L. C., Rahman, I. A., Asmi, A., Nagapan, S., & Khalid, K. I. (2013). Classification and Quantification of Construction Waste at Housing Project Site. *International Journal of Zero Waste Generation, 1*(1).

Franklin Associates, P. V., KS. (1998a). CHARACTERIZATION OF BUILDING-RELATED CONSTRUCTION AND DEMOLITION DEBRIS IN THE UNITED STATES. *The U.S. Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste*.

Franklin Associates, P. V., KS. (1998b). Characterization of building-related construction and demolition debris in the United States. (EPA530-R-98-010). (accessed October 28, 2015)

Goedkoop, M. J. H., R.; Huijbregts, M.A.J.; De Schryver, A.M.; Struijs, J.; Van Zelm, R. (2009). ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level from Netherlands: http://www.lcia-recipe.net. (accessed Jan 19, 2017)

Hassan, M. N., Rahman, R. A., Chong, T. L., Zakaria, Z., & Awang, M. (2000). Waste recycling in Malaysia: problems and prospects. *Waste Management and Research, 18*(4), 320-328.

ISO14040. (2006). Environmental management — Life cycle assessment — Principles and framework.

ISO14044. (2006). Environmental management — Life cycle assessment — Requirements and guidelines.

Jaillon, L., Poon, C. S., & Chiang, Y. H. (2009a). Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management, 29*(1), 309-320.

Jaillon, L., Poon, C. S., & Chiang, Y. H. (2009b). Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Manag, 29*(1), 309-320.

JIWIC. (2015). Weight conversion coefficient of industrial waste (in Japanese). Retrieved from http://www.jwnet.or.jp/jwnet/pdf/gyouseihoukoku_jyuuryoukanzankeisuu.pdf (accessed December 24, 2015)

Kloepffer, W. (2008). Life cycle sustainability assessment of products. *The International Journal of Life Cycle Assessment, 13*(2), 89.

Knoeri, C., Sanyé-Mengual, E., & Althaus, H.-J. (2013). Comparative LCA of recycled and conventional concrete for structural applications. *The International Journal of Life Cycle Assessment, 18*(5), 909-918.

Kourmpanis, B., Papadopoulos, A., Moustakas, K., Stylianou, M., Haralambous, K. J., & Loizidou, M. (2008). Preliminary study for the management of construction and demolition waste. *Waste Management & Research, 26*(3), 267-275.

Lachimpadi, S. K., Pereira, J. J., Taha, M. R., & Mokhtar, M. (2012). Construction waste minimisation comparing conventional and precast construction (Mixed System and IBS) methods in high-rise buildings: A Malaysia case study. *Resources, Conservation and Recycling, 68*(0), 96-103.

Lau, H. H., Whyte, A., & Law, P. L. (2008). Composition and Characteristics of Construction Waste Generated by Residential Housing Project. *International Journal of Environmental Research, 2*(3), 8.

Laurent, A., Bakas, I., Clavreul, J., et al. (2014). Review of LCA studies of solid waste management systems – Part I: Lessons learned and perspectives. *Waste Management, 34*(3), 573-588.

Lee, C. F., Rahman, I. A., Asmi, A., Nagapan, S., & Khalid, K. I. (2013). Classification and Quantification of Construction Waste at Housing Project Site. *International Journal of Zero Waste Generation, 1*(1).

Llatas, C. (2011). A model for quantifying construction waste in projects according to the European waste list. *Waste Management, 31*(6), 1261-1276.

Llatas, C. (2013). Methods for estimating construction and demolition (C&D) waste. In F. P.-T. W. Y. T. A. L. D. d. Brito (Ed.), *Handbook of Recycled Concrete and Demolition Waste* (pp. 25-52): Woodhead Publishing.

Lu, W., Yuan, H., Li, J., Hao, J. J. L., Mi, X., & Ding, Z. (2011). An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. *Waste Management, 31*(4), 680-687.

Ma, F., Sha, A., Yang, P., & Huang, Y. (2016). The Greenhouse Gas Emission from Portland Cement Concrete Pavement Construction in China. *International Journal of Environmental Research and Public Health, 13*(7), 632.

Mah, C. M., & Fujiwara, T. (2015). Survey of Construction Waste of High Rise Mixed-Use Development in Malaysia (京都大学環境衛生工学研究会 第 37 回シンポジウム講演論文集). *環境衛生工学研究 : 京都大学環境衛生工学研究会機関誌, 29*(3), 23-26.

Mah, C. M., Fujiwara, T., & Ho, C. S. (2016). Construction and Demolition Waste Generation Rates For High-Rise Buildings in Malaysia. *Waste Management & Research*.

Mah, C. M., Fujiwara, T., & Ho, C. S. (2017). Concrete Waste Management Decision Analysis Based On Life Cycle Assessment. *Chemical Engineering Transactions, 56*.

Mahayuddin, S. A., & Zaharuddin, W. A. Z. W. (2013). Quantification of waste in conventional construction. *International Journal of Environmental Science and Development, vol. 4*(no. 3), 4.

Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management, 30*(11), 2255-2264.

Marinković, S. B., Ignjatović, I., & Radonjanin, V. (2013). 23 - Life-cycle assessment (LCA) of concrete with recycled aggregates (RAs) A2 - Pacheco-Torgal, F. In V. W. Y. Tam, J. A. Labrincha, Y. Ding, & J. d. Brito (Eds.), *Handbook of Recycled Concrete and Demolition Waste* (pp. 569-604): Woodhead Publishing.

Martinez-Sanchez, V., Kromann, M. A., & Astrup, T. F. (2015). Life cycle costing of waste management systems: Overview, calculation principles and case studies. *Waste Management, 36*, 343-355.

Marzouk, M., & Azab, S. (2014). Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. *Resources, Conservation and Recycling, 82*(Supplement C), 41-49.

McDonald, B., & Smithers, M. (1998). Implementing a waste management plan during the construction phase of a project: a case study. *Construction Management and Economics, 16*(1), 71-78.

Mercante, I. T., Bovea, M. D., Ibáñez-Forés, V., & Arena, A. P. (2012). Life cycle assessment of construction and demolition waste management systems: a Spanish case study. *The International Journal of Life Cycle Assessment, 17*(2), 232-241.

MLIT. (2014). White Paper on Land, Infrastructure, Transport and Tourism in Japan 2014. Japan: Ministry of Land Infrastructure Transport and Tourism, MLIT Retrieved from http://www.mlit.go.jp/common/001063075.pdf (accessed 01.10.2016)

Musa, M. F., Mohammad, M. F., Mahbub, R., & Yusof, M. R. (2014). Enhancing the Quality of Life by Adopting Sustainable Modular Industrialised Building System (IBS) in the Malaysian Construction Industry. *Procedia - Social and Behavioral Sciences, 153*, 79-89.

Myers, D. (2017). *Construction Economics - a new approach* (4th ed.). London and New York: Routledge - Taylor & Francis Group

NAHB (1997) Residential construction waste management. A builder's field guide - how to save money and landfill waste. From National Association of Home Builders, Publications http://www.branz.co.nz/cms_display.php?sn=105&pg=12672 (accessed December 2, 2015)

The solid waste and public cleansing management Act 2007 (Act 672), Part 1.1(3) C.F.R. (2007).

NEA. (2016). Waste statistics and overall recycling. Singapore: National environment agency Retrieved from http://www.nea.gov.sg/energy-waste/waste-management/waste-statistics-and-overall-recycling (accessed May 24, 2017)

Ondova M., S. N. (2013). Environmental assessment of fly ash concrete. *Chemical Engineering Transactions, 35*, 841-846.

Ortiz, O., Pasqualino, J. C., & Castells, F. (2010). Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain. *Waste Management, 30*(4), 646-654.

Pasqualino, J. C., Ortiz, O. O., & Castells, F. (2008). Life cycle assessment as a tool for material selection and waste management within the building sector. *PLEA 2008 – 25th Conference on Passive and Low Energy Architecture*, Dublin.

Petrolpricemalaysia (2017) Petrol price in Malaysia. From Publications http://petrolpricemalaysia.info/ (accessed

Poon, C. S., & Chan, D. (2007). The use of recycled aggregate in concrete in Hong Kong. *Resources, Conservation and Recycling, 50*(3), 293-305.

Poon, C. S., Yu, A. T. W., & Jaillon, L. (2004). Reducing building waste at construction sites in Hong Kong. *Construction Management and Economics, 22*(5), 461-470.

Poon, C. S., Yu, A. T. W., & Ng, L. H. (2001). On-site sorting of construction and demolition waste in Hong Kong. *Resources, Conservation and Recycling, 32*(2), 157-172.

PRé, v. a. (2016). SimaPro Database Manual - method library. from https://www.pre-sustainability.com/download/DatabaseManualMethods.pdf (accessed May 28, 2017)

Rigamonti, L., Grosso, M., & Sunseri, M. C. (2009). Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems. *The International Journal of Life Cycle Assessment, 14*(5), 411-419.

Ristimäki, M., Säynäjoki, A., Heinonen, J., & Junnila, S. (2013). Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy, 63*, 168-179.

Rosado, L. P., Vitale, P., Penteado, C. S. G., & Arena, U. (2017). Life cycle assessment of natural and mixed recycled aggregate production in Brazil. *Journal of Cleaner Production, 151*, 634-642.

Sealey, B. J., Phillips, P. S., & Hill, G. J. (2001). Waste management issues for the UK ready-mixed concrete industry. *Resources, Conservation and Recycling, 32*(3–4), 321-331.

Simion, I. M., Fortuna, M. E., Bonoli, A., & Gavrilescu, M. (2013). Comparing environmental impacts of natural inert and recycled construction and demolition waste processing using LCA. *Journal of Environmental Engineering and Landscape Management, 21*(4), 273-287.

Teo, M. M. M., & Loosemore, M. (2001). A theory of waste behaviour in the construction industry. *Construction Management and Economics, 19*(7), 741-751.

Tošić, N., Marinković, S., Dašić, T., & Stanić, M. (2015). Multicriteria optimization of natural and recycled aggregate concrete for structural use. *Journal of Cleaner Production, 87*, 766-776.

UNCRD. (2015). *3R as an economic industry - next generation 3r solutions for a resource efficient society and sustainable tourism development in asia and the pacific*. Paper presented at the Sixth Regional 3R Forum in Asia and the Pacific, Malé, Maldives, 9-10,United nations centre for regional development

USEPA. (2003). Building related construction and demolition materials amounts. from (accessed

USEPA. (2016a). Construction and Demolition Materials. USA: USEPA Retrieved from https://www.epa.gov/sites/production/files/2016-03/documents/warm_v14_construction_demolition_materials.pdf (accessed 01.09.2016)

USEPA. (2016b). Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM). from United States:

https://www.epa.gov/sites/production/files/2016-03/documents/warm_v14_construction_demolition_materials.pdf (accessed

USGBC, U. S. G. B. C. (2006). Construction and Demolition Waste Management. from http://www.eesi.org/files/climate.pdf (accessed November 15, 2015)

USLCI. (2013). The US life cycle inventory database version 2013 NAtional Renewable Energy laboratory Retrieved from https://uslci.lcacommons.gov/uslci/search

Wang, J., Yuan, H., Kang, X., & Lu, W. (2010). Critical success factors for on-site sorting of construction waste: A china study. *Resources, Conservation and Recycling, 54*(11), 931-936.

Wang, J. Y., Touran, A., Christoforou, C., & Fadlalla, H. (2004). A systems analysis tool for construction and demolition wastes management. *Waste Management, 24*(10), 989-997.

Zealand, C. C. C. A. o. N. (2011). Recycled Aggregates in New Concrete. from New Zealand: www.ccanz.org.nz/files/documents/ad659c71-06cb-44b1-95dd-7b7350fdcd54/TR_14_Recycled_Aggregates_in_New_Concrete_2013.pdf (accessed 07.07.2016)

Zeng, N. (2008). Carbon sequestration via wood burial. *Carbon Balance and Management, 3*, 1-1.